

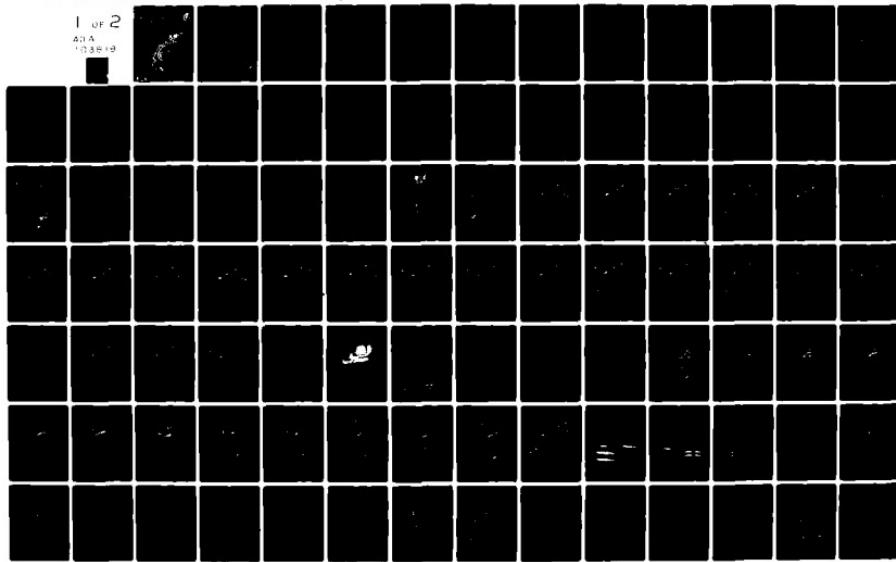
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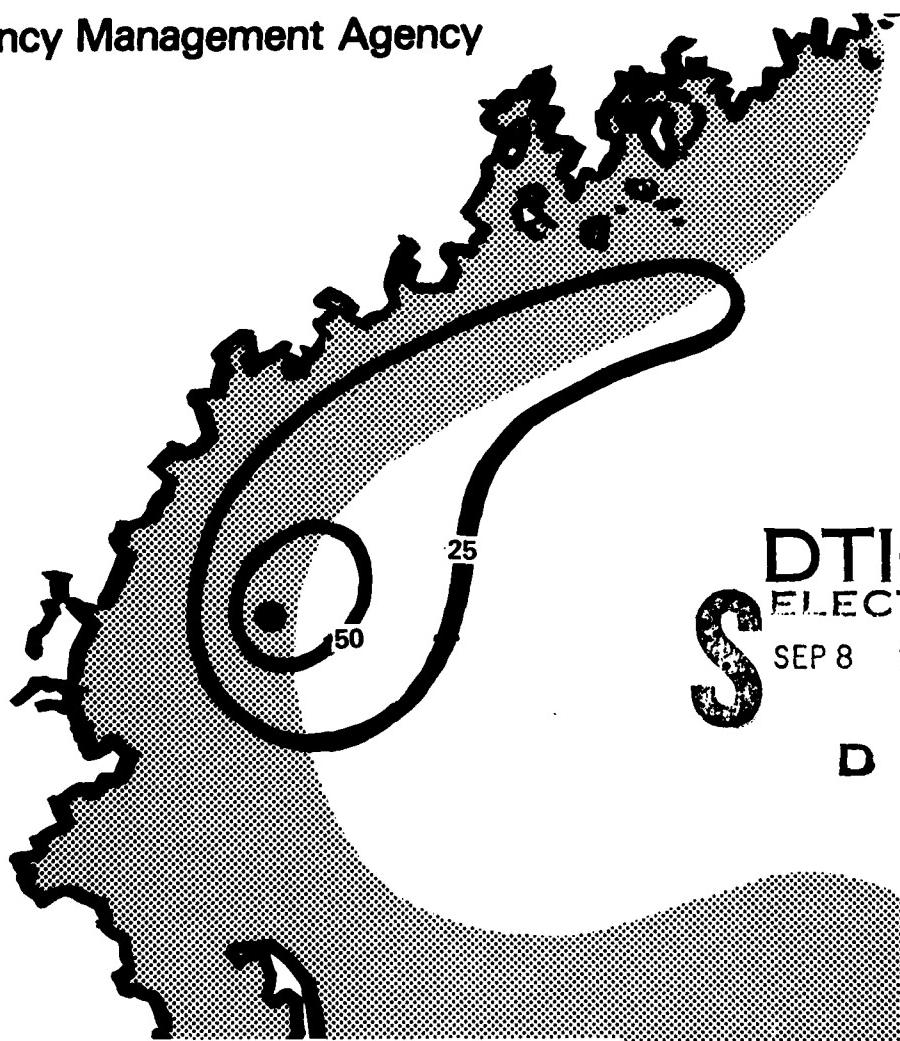
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# A Climatological Oil Spill Planning Guide

No. 2

Gulf of Maine / Georges Bank

Federal Emergency Management Agency



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Report to Regional Response Team,  
Coastal Regional I,  
First Coast Guard District.

## A Climatological Oil Spill Planning Guide.

Number

No. 2 -  
Gulf of Maine / Georges Bank.

Compiled by Joseph M. Bishop  
Donna Harrigan  
Vanessa Mello

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## 1. INTRODUCTION

Oil spills are a major concern in both offshore oil production and oil transport at sea. For an effective oil spill contingency plan to be formulated, one needs relevant environmental data. The objective of this study is to provide such information in a format that can be understood and used by decision makers in oil spill contingency planning and by scientific support personnel during actual spills. The concept that a report of this type should be available was initially developed during the grounding of the Argo Merchant. At that time it became apparent that there was no source of key climatological data available for pre-spill planning and post-spill mitigation purposes. This planning guide discusses the movement of oil at sea, presents relevant environmental data, and predicts the possible impact of oil spills on the marine environment. The hope is to provide the necessary environmental information to help mitigate adverse effects in the event of a major oil spill. The guide can also be used for spills of other types such as hazardous chemicals, since many of the governing environmental processes and impacted resources would be the same.

This report is the second in a series designed to cover all U.S. Regional Response Areas. The first planning guide covered the New York Bight (Coastal Region II); this report is for the Gulf of Maine/Georges Bank (Coastal Region I).

## 2. FATE OF OIL AT SEA

### 2.1 Introduction

Environmental processes determine the movement and modification of oil spilled at sea. After a large spill, the oil begins to spread over the sea surface, rapidly at first, then more slowly. In a few hours, it forms a slick. Evaporation and the dissolving of some oil components leave a residue with chemical properties differing from those of the original oil. Chemical and biological degradation may occur along with the formation of water-in-oil emulsions. The size and thickness of a slick will influence the rate of these processes. Wind and waves tend to break up the slick into patches that are eventually advected and diffused from the spill site. All these interactions result in changes of the oil's properties and thus influence the final fate of oil at sea. In general, the primary factors concerning oil fate, as illustrated in figure 1, are:

- Spreading
- Advection
- Turbulent diffusion
- Emulsion formation
- Photochemical oxidation
- Solution and dispersion
- Microbiological action
- Evaporation
- Aerosol formation
- Subsurface Transport
- Sedimentation

### 2.2 Spreading

Theoretical attempts to describe the spreading of an oil slick have been unsophisticated and are generally considered to be of marginal value for use at sea. The commonly used Fay (1969) theory postulates that oil spreads in three stages (Figure 2). This diagram might be of limited use to estimate the amount of cleanup resources required by giving estimates of spill size and thickness.

Oil weathering processes influence oil spreading. Weathering and emulsification, for instance, decrease the spread of oil. This is due to an increase in density and viscosity as the oil forms into lumps and smaller individual slicks.

Surface film formation lessens spreading, acting as a "chemical boom" that traps the spreading oil. Other physical parameters, such as temperature and salinity, influence oil spreading. In turn, spreading will influence some weathering processes, including the rates of evaporation and dissolution.

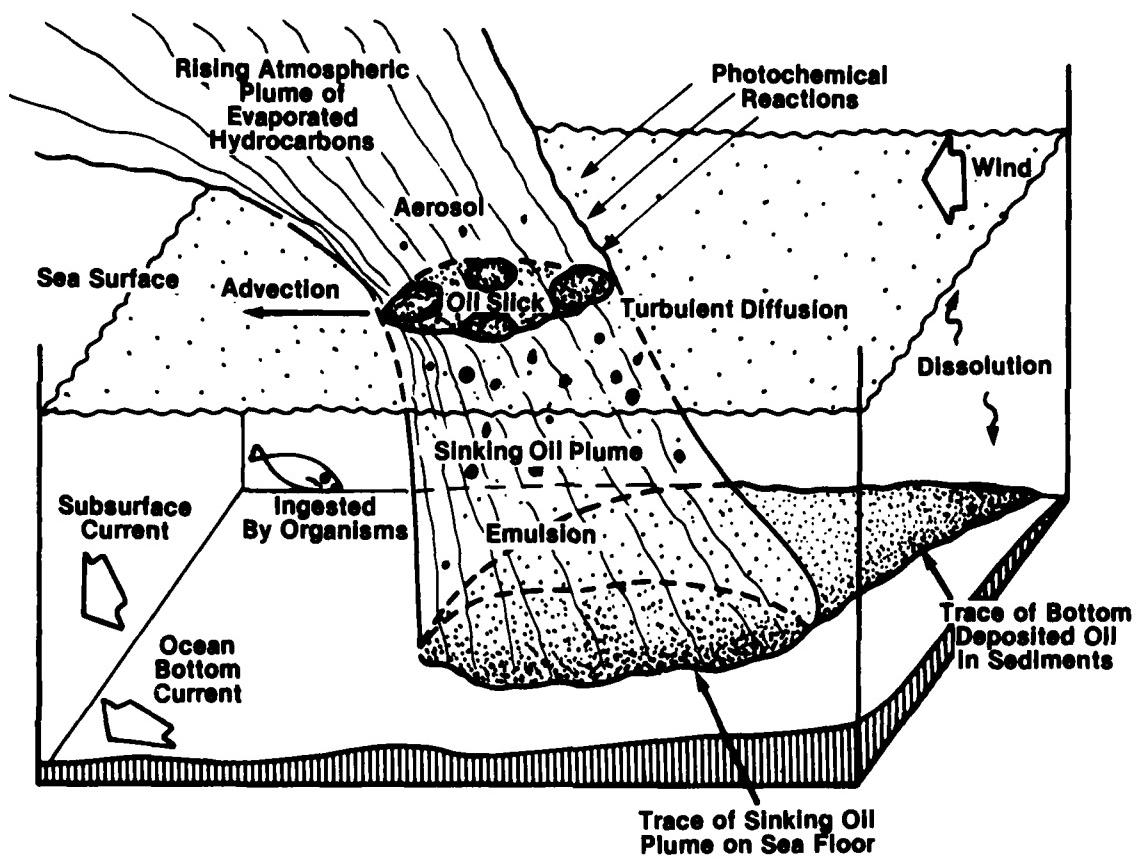


Figure 1.--Block diagram showing the fate of an oil slick (after Kolpack and Plutchak, 1976).

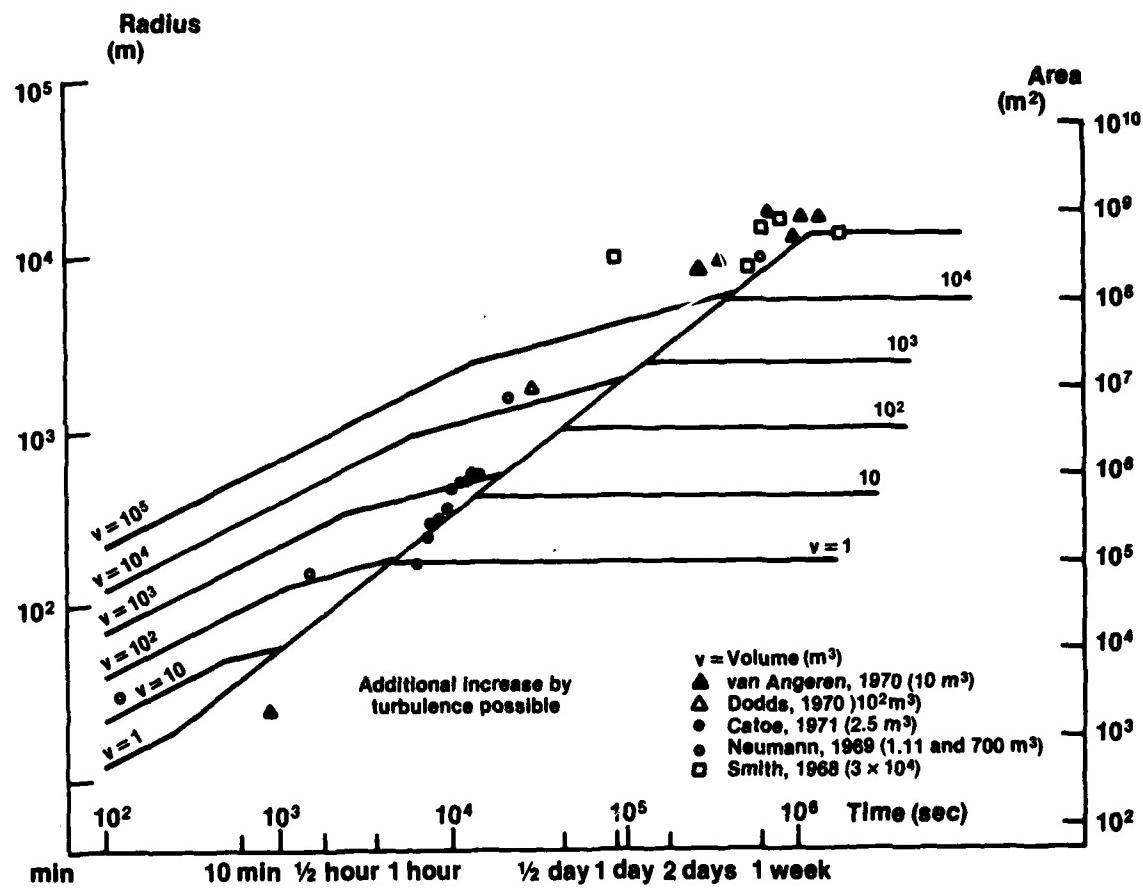


Figure 2.--The spreading of an oil slick as function of time (Otto, 1973).

### 2.3 Advection

Predicting the advection of an oil slick by currents is critical for impact mitigation procedures to be most effective. When estimating advection, one must first understand its relationships to the averaging interval. Currents that occur at intervals equal to or less than that time may result in either no net movement (if they are periodic) or a diffusive effect (if they are random). In estimating oil spill advection over a large distance, one usually uses atlas values that have been averaged seasonally over many years of observations. These currents are termed permanent currents. For this interval, tidal currents are periodic; and transient wind-driven currents have a random, nonadvective component. One must be careful here. For example, if the oil is near the coast, the tidal current and/or "random" winddrift may drive the oil slick onshore over a shorter than advective time-scale. Thus, these types of periodic and random motions become important for advection near impact points.

Current convergence lines may act as a natural "boom" that inhibits advection. Furthermore, oil may be vertically dispersed as small droplets suspended in water when turned under by wave and surf action. Once in deeper waters, the oil is advected away from the surface oil by sub-surface currents. Techniques to estimate oil spill advection will be discussed in more detail in section 2.13.

### 2.4 Turbulent Diffusion

Environmental action causes oil slicks to break up into patches. These patches are generally advected with the permanent current, but they are also subjected to random eddies in the current field which spread the patches over a large area. The rate of spreading of these patches over various time and space scales has been roughly estimated (Figure 3). For example, oil patches will be dispersed to an area of about  $10^9 \text{ cm}^2$  (i.e., a radius of about a kilometer) in approximately one day because of ambient turbulence.

### 2.5 Emulsion Formation

A short time after the spill, the heavier oil fractions will take on a highly viscous consistency caused by the formation of a water-in-oil emulsion termed "mousse". Lumps of oil in this form will persist for months in the sea and may be advected to distant shorelines. An oil-in-water emulsion can also exist with the oil in suspension. A thicker slick and agitated sea state favor emulsion formation.

### 2.6 Photochemical Oxidation

The less volatile fractions of oil are hydrocarbons whose solubility in water is slight. Under the influence of sunlight, however, these fractions can react with atmospheric oxygen to produce more soluble compounds. This

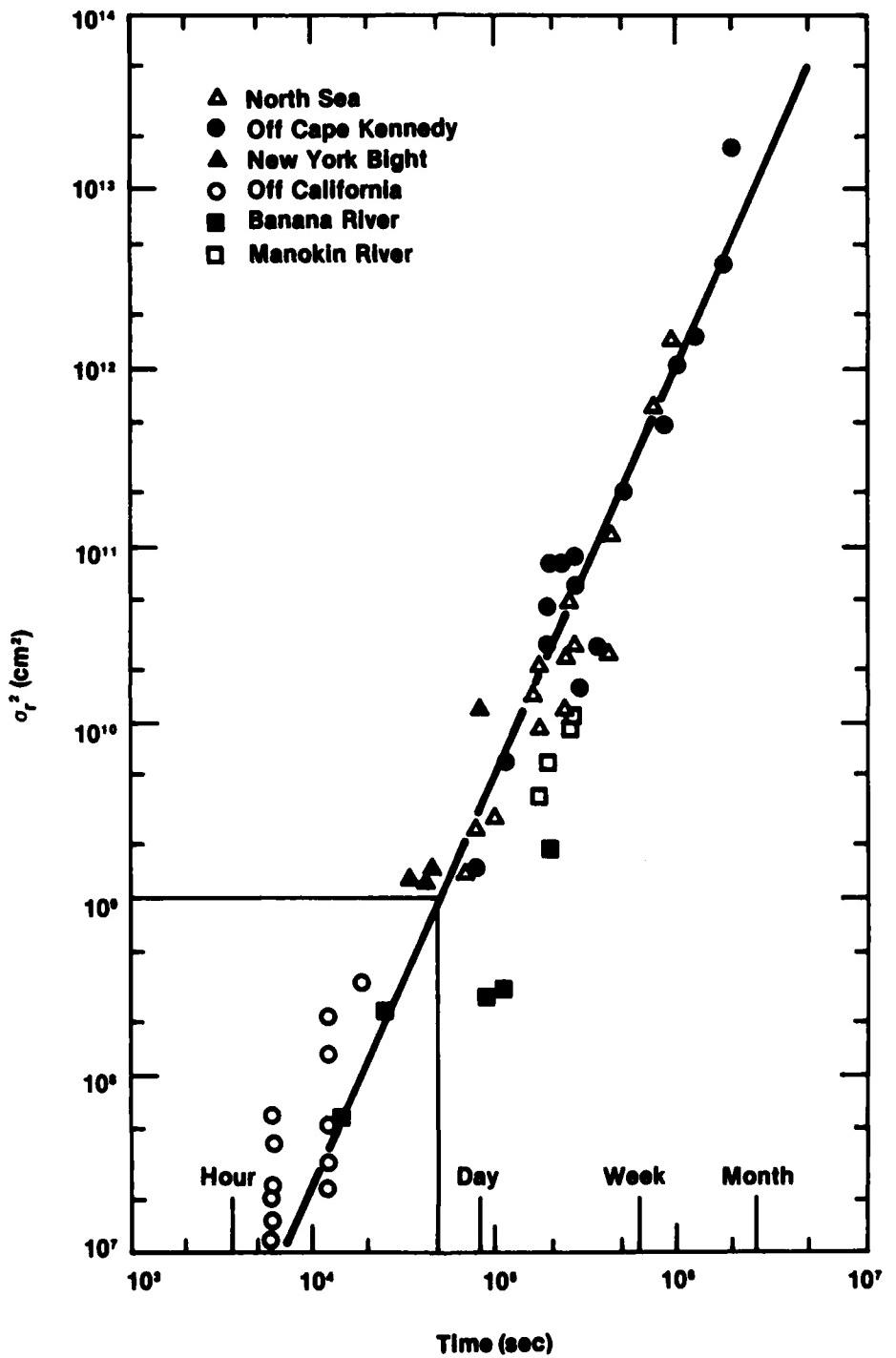


Figure 3.--Surface dye patch size,  $\sigma_r^2$ , as a function of time (after Okubo, 1962).

process is small and becomes important only when oil is spread in a thin film. Photochemical oxidation may become a factor in breaking down slicks a few microns thick.

Photo-oxidation operates mostly after the first 24 to 48 hours; thus, the lighter, volatile fractions of oil that rapidly evaporate within the first 24 hours leave the slick before being transformed by this process.

Environmental factors such as temperature influence the removal rate of oil by chemical decomposition. Low temperatures result in a low rate of removal because of decreased reaction rates. Temperatures below 5 C lead to no significant chemical breakdown of the oil.

#### 2.7 Solution and Dispersion

A small amount of the oil slick may actually pass into solution in sea-water. This may constitute a larger pollution hazard because this is the easiest state for interaction with marine organisms. The solubility of hydrocarbons is small when compared with the amount of oil dispersed as fine droplets. Solution and dispersion processes move oil from the slick to the water column. Sea state (wave height) is the most important environmental condition governing these processes and may lead to concentrations of oil of up to 10ppm to depths of a few meters below a slick. Dispersed oil can easily be ingested by marine organisms.

#### 2.8 Microbiological Action

Seawater contains many species of bacteria, molds, and yeasts capable of attacking oil. As with photochemical oxidation, biological processes are slowed by low temperatures or high pressures. Below 1,000 meters, there is only slight microbial activity. These organisms, which are more numerous in coastal waters than in the open sea, use hydrocarbons as an energy source; but their activity depends on a plentiful supply of nutrients. Nutrient and oxygen levels are directly proportional to the removal of spilled oil by microbiological action. Therefore, oil in deep waters will persist for long periods, and even under the most favorable conditions, a period of months is required to remove a large portion of a slick.

#### 2.9 Evaporation

A surface oil slick will lose mass through surface evaporation. The amount of loss is related directly to the carbon number of the oil fraction in question. It also depends on environmental factors such as wind speed and the amount of wind-wave white capping; thus, increased wind speed results in greater evaporation of the volatile components in the oil.

## 2.10 Aerosol Formation

Strong water agitation due to wave action leads to bubbling of the water at the sea surface. This allows oil at the sea surface to leave the water as an aerosol. Although this process is usually negligible, it becomes increasingly important as rougher seas persist. Studies have shown that solar radiation enhances this effect.

## 2.11 Subsurface Transport

Mixing of a surface oil slick can easily result in diffusion of oil into the water column where it can be transported over considerable distances. Orbital motion of surface waters as a result of wave action can result in the transport of oil to depths of several tens of meters. Such oil in the form of droplets can rapidly achieve a density close to that of the surrounding water. In such a relatively neutral state of buoyancy, droplets can then move for many miles before they are consumed by microorganisms, partially dissolved, or deposited on the ocean floor or a coastline.

Once submerged, oil may cool sufficiently or adhere to particulate matter so that it sinks deeper into the water column. Since the sinking process may take place very slowly, the ultimate deposition of the oil may occur far from the actual spill site. The processes which can act on oil at the water surface and move it into the water column are capable of removing fresh surface oil as well as old weathered oil, emulsions, discrete subsurface globules, and dissolved components of oil.

## 2.12 Sedimentation

Another process that involves the removal of oil from a surface slick is that of sedimentation, or the attachment of oil to suspended particulate matter in the water column. While relatively little is known about this process, observations during accidental and experimental spills have shown oil has a tendency to adhere to organic material, silt, sand, and even shell fragments.

It has been observed that the amount of oil adsorbed by water-borne sediments normally increases as the size of the sediment grains decreases--on a unit mass basis, the smaller the grains, the more total surface area there is for attachment. For this reason, fine-grained minerals are thought to be capable of removing large volumes of oil from the surface and distributing that oil in the water column or on the ocean floor. However, fine, suspended sediments do not always account for the removal of oil from the surface. The age of the sediments, and therefore the amount of accumulated organic matter on their surfaces, strongly influences the extent to which they can absorb oil. Thus, "young" sediments such as those associated with glacial silt may have very little effect upon the removal of surface slicks through sedimentation. Turbulent mixing of an oil film down into the water column may well be the reason why observers frequently associate the removal of oil from the surface with the process of sedimentation.

## 2.13 Factors Influencing Real-Time Oil Spill Mitigation

At times an estimate of the fate of spilled oil is needed before qualified scientific advice can be received. In this case, estimated trajectories might be helpful in cleanup operations. In this section, several environmental factors influencing oil spills will be discussed in the overall context of oil spill mitigation.

First, the spill type (continuous, noncontinuous, collision, grounding, leakage, hose rupture, etc.), size and location should be determined. The type of spill often dictates the volume of discharged oil. Usually, an estimate of spill volume can be calculated once the spill type and ship size are known. If the facts about the spill are unknown, a rough estimate of spill size can be made by air, the oil slick's surface area and approximate thickness being the two pertinent factors in this calculation.

Estimates of the size and volume of an oil spill are important for a number of reasons. The transport, modification, and ultimate disposition of a spill, for example, depend in part upon the areal extent and thickness of the spill throughout its existence. These factors, in turn, influence the many decisions involved in the planning of an effective oil spill containment and recovery operation. Spill size and volume estimates are also essential for identifying probable oil spill impact zones, types of impact, and possible means of eliminating or reducing such impact. These considerations, together with the obvious role that size and volume estimates play in documentation and litigation matters, suggest that simple techniques be developed for such estimations.

Conversion Factors - Table 1 contains conversion factors to facilitate estimations of spill size and volume as needed.

Volume/Color/Thickness Relationships - The volume of oil contained in a surface slick can be expressed as:

$$V = (A) (t)$$

where,  $V$  = Volume ( $m^3$ )  
 $A$  = Area of slick ( $m^2$ )  
 $t$  = Thickness of slick (m)

Since observations and estimates rarely involve the same basic units for each of the above parameters, the following expression is provided using the same equation with more common units:

$$V = (4.14 \times 10^5) (A) (t)$$

where,  $V$  = Volume (barrels)  
 $A$  = Area of slick ( $miles^2$ )  
 $t$  = Thickness of slick (inches)

TABLE 1  
APPROXIMATE CONVERSION FACTORS FOR CRUDE OIL

TO CONVERT	INTO					1,000	1,000
	Metric Tons	Long Tons	Short Tons	Barrels	Kiloliters (cu. m.)	Gallons (Imp.)	Gallons (U.S.)
<b>MULTIPLY BY</b>							
Metric Tons	1	0.984	0.102	7.30	1.16	0.255	0.306
Long Tons	1.016	1	1.120	7.42	1.18	0.260	0.312
Short Tons	0.907	0.893	1	6.63	1.05	0.231	0.277
Barrels	0.137	0.135	0.151	1	0.159	0.035	0.042
Kiloliters (cu. m.)	0.863	0.849	0.951	6.29	1	0.220	0.264
1,000 Gallons (Imp.)	3.92	3.86	4.32	28.6	4.55	1	1.201
1,000 Gallons (U.S.)	3.62	3.21	3.6	23.8	3.79	0.833	1
<b>FROM</b>							
TO CONVERT	Barrels to Metric Tons	Metric Tons to Barrels	Barrels/Day to Tons/Year	Tons/Year to Barrels/Day			
<b>MULTIPLY BY</b>							
Crude Oil	0.137	7.30	50.0	0.0200			
Motor Spirit	0.118	8.45	43.2	0.0232			
Kerosene	0.128	7.80	46.8	0.0214			
Gas/Diesel	0.133	7.50	48.7	0.0205			
Fuel Oil	0.149	6.70	54.5	0.0184			
To Convert	Multiply By	To Obtain					
Acres	$4.35 \times 10^4$	Square feet					
Acres	$1.562 \times 10^{-3}$	Square miles					
Barrels (U.S.)	42	Gallons (U.S.)					
Cubic feet	7.48	Gallons (U.S.)					
Feet/second	$5.921 \times 10^{-1}$	Knots					
Feet/second	$6.818 \times 10^{-1}$	Miles/hour					
Knots	$6.076 \times 10^3$	Feet/hour					
Knots	1.151	Statute miles/hour					
Mile (nautical)	$2.0254 \times 10^3$	Yards					
Miles/hour	88	Feet/minute					
Square feet	$3.587 \times 10^{-8}$	Square miles					
Square feet	$6.40 \times 10^2$	Acres					

Using the above equation, a slick covering an area of approximately 1 square mile with an average thickness of  $10^{-3}$  inch (or 1/1000 inch) would contain about 414 barrels of oil. Iridescent (or rainbow colored) films are typically on the order of a hundred thousandth ( $10^{-5}$ ) of an inch thick, resulting in only about 4 barrels per square mile. At thicknesses on the order of one thousandth ( $10^{-3}$ ) of an inch or more, dark oils (e.g., crude and bunker C) begin to appear their natural dark blue/black color, resulting in volumes of approximately 400 barrels of oil per square mile or more.

Open Water Estimates - The estimation of oil slick volumes associated with open water conditions is difficult because there are rarely good reference points (such as docks, ships, and drilling platforms) nearby. Without such objects to aid in the estimation of slick dimensions, area estimates and thus volume calculations, may be inaccurate.

When observations and/or photographs can be obtained with sufficient scaling information (piers, marker buoys, camera angle and altitude, etc.), rough estimates can be made of a slick's approximate area by envisioning or sketching simple boxes, circles, or triangles of a comparable size around the slick or its component subslicks.

The spill location helps to predict the impact of the oil both in the water and along the shoreline. A simplified methodology used to predict advection from the spill site is vector addition. (See figures 4a and 4b.) The wind driven current and permanent current are the major driving mechanisms acting upon oil movement. They are represented as vectors with their starting points (origins) on the spill location, oriented in the direction of propagation, with a vector length proportional to their speeds. The resultant vector is the predicted oil advection. (Figure 4c.)

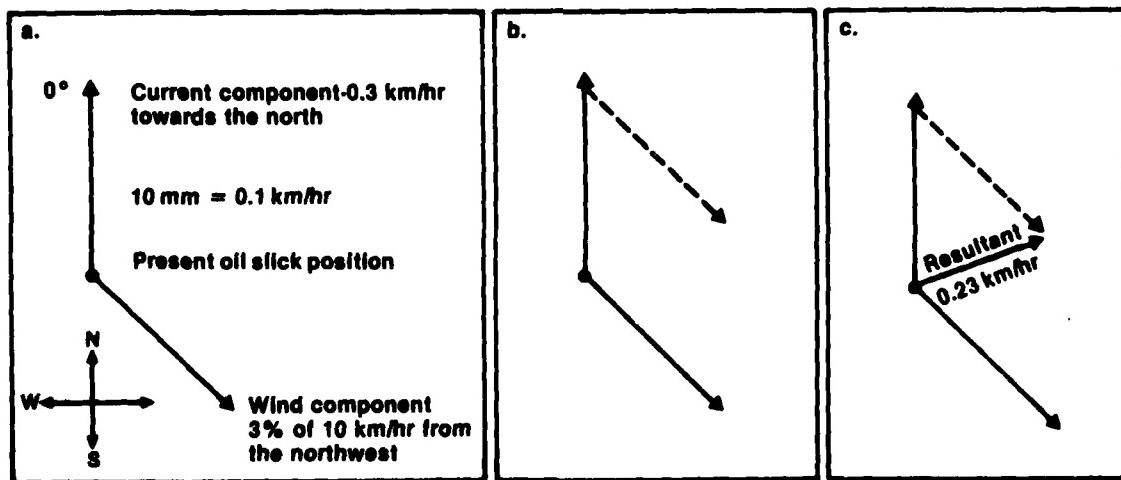


Figure 4.--Vector addition for 10 km/hr northwest wind current and 0.3 km/hr north permanent current (from Woodward-Clyde, 1979).

Consider the following first-order approximation for advection in coastal water (i.e. depth < 200 m). In the absence of a strong permanent current, both empirical and theoretical studies have shown that an oil slick on the ocean surface travels at about 3 percent of the wind speed, directed at a slight angle (within 15° to the right, in the northern hemisphere) of the downwind direction.

In regions having strong permanent currents, such as the Gulf Stream, available atlas presentations or satellite data should be consulted. In general, the Gulf Stream is visible on the satellite photograph as a dark region about 100 km wide with the peak current (core) about 30 km from the shoreward boundary. A peak current of about 150 cm/sec can be assumed for the core. The advection can be approximated as the vectorial sum of the wind-driven current and the permanent current. If the oil spill is within a tidal excursion to the impact point, an estimate of tidal current may also be added to the current vector.

Another important operational consideration is the distance between spill site and impact and how this relates through various environmental processes to the time of impact. Figure 5 indicates these relationships by plotting the important environmental processes on a space-time chart. One need only estimate the distance to the impact points and the advection velocity toward impact. The diagram indicates impact time and the various physical processes of importance for those length and time scales. For example, a consideration of tidal currents is needed only at a distance of  $10^3$  to  $10^4$  m from spill impact.

Another concern, when developing a real-time oil spill mitigation plan, is the type of oil discharged. Various classifications of oil will interact differently with the environment and will require different cleanup approaches. Oils can be divided into four general categories. (See Table 2).

Class 1 oils are the light, volatile oils. Typical of these are the diesel oils and many of the light crude oils. Since Class 1 oils readily penetrate porous surfaces, they may persist in a contaminated substrate. Fresh, volatile oils are extremely toxic and form unstable emulsions.

Class 2 oils consist of the medium to heavy paraffin base oils and the fluid emulsified oils. The penetrating tendency is directly proportional to temperature. Equally variable is the toxicity of Class 2 oils. Weathering modifies the most toxic elements and, with low temperatures, may change the class of the oil.

The third class of oils is composed of the residual fuel oils and asphaltic and mixed-base oils in the fluid state, as well as the water-in-oil emulsions with high water contents. The biological effects of Class 3 oils are related to smothering and coating rather than the toxicity of the oil.

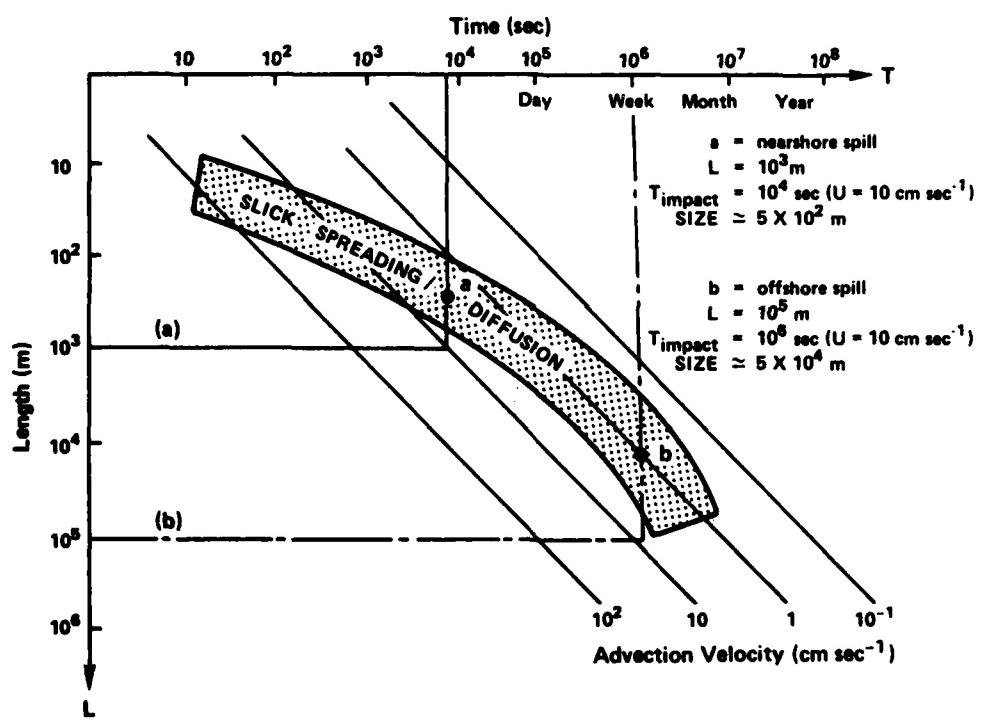


Figure 5.--Time-length scales connected with oil spills of various distances from shore.

The penetrating ability of Class 3 oils is slight. Many of these oils sink in the ocean due to specific gravities near or exceeding that of water. This phenomenon leads to tar- or asphalt-like balls of oil in the Class 4 range.

Class 4 oils include the residual oils, heavy crude oils, some high paraffin crude oils, and weathered oils that are solid or nonfluid. Solid forms are virtually nontoxic.

A third concern in real-time spill mitigation is the assessment of shoreline characteristics. This includes the type of substrate encountered, the degree of shoreline exposure, and the wave energy of the region. The oil's total duration in the coastal environment is affected by this parameter.

Different substrates have varying properties that affect the oil's residence time (e.g. absorption, grain size, resistance, etc.). Substrate classification includes mud, sand, gravel, cobble, boulders, rocks, marine terraces, and man-made structures. (See Table 3.)

An unprotected shoreline lends itself to the full impact of oil contamination. A sheltered area is less subject to pollution. Similarly, wave energy, height, and period contribute to oil deposition.

Figure 6 illustrates the beach classification for the study area. In general, the Gulf of Maine coastline north of Boston Harbor is rocky. This fact aids the decision maker when confronted with possible oil contamination or post-impact cleanup, for rocky shorelines are less affected by oil. There is a good probability of low persistence of the oil and thus of an expedient cleanup, as oil will most likely seep between the rocks. There is generally high biological value associated with this type of unsheltered, rocky shorelines.

South of Boston Harbor, either sand beaches or pocket beaches predominate. Contamination for sandy beaches is more severe and more noticeable than for rocky shores. Oil penetrates the beach and tends to persist. Moreover, such beaches are thought to have a low biological value.

Pocket beaches are rather well protected from oil pollution, yet when oil does reach these areas, it persists for long periods due to relatively low wave energy. The sheltered coast is less easily impacted and less easily cleaned once impacted. Depending on the substrate categorization, these beaches can suffer any range of effects due to oil spill contamination. The biological value of the beach differs with beach type as well.

Generally, the longer the oil persists the greater is the penetration and/or buried state. Class 1 oils penetrate sand or mud substrates quite rapidly. Class 2, 3, and 4 oils do not. The most rapid oil penetration occurs in large grain size beaches.

TABLE 2 SPILL RESPONSE OIL CLASSIFICATION  
(from Woodward-Clyde, 1979)

Determined Oil Type Designation	Oils	Representative Diagnostic Properties	Physical/Chemical Properties
1 Light volatile oils	Distillate fuel and most light crude oils	Highly fluid, usually transparent but can be opaque, strong odor, rapid spreading, can be rinsed from plant sample by simple agitation.	May be flammable, high rate of evaporative loss of volatile components, assumed to be highly toxic to marine or aquatic biota when fresh, tend to form unstable emulsions, may penetrate substrates.
2 Non-sticky oils	Medium to heavy paraffin-base refined and crude oils	Moderate to high viscosity, waxy or oily feel, can be rinsed from surfaces by low pressure water flushing.	Generally removable from surfaces, penetration of substrates variable, toxicity variable, includes water in oil emulsions.
3 Heavy, sticky oils	Residual fuel oils; medium to heavy asphaltic and mixed-base crudes	Typically opaque brown or black, sticky or tarry, viscous, cannot be rinsed from plant sample by agitation.	High viscosity, hard to remove from surfaces, tend to form stable emulsions, high specific gravity and potential for sinking after weathering, low substrate penetration low toxicity (biological effects due primarily to smothering), will interfere with many types of recovery equipment.
4 Nonfluid oils (at ambient temperature)	Residual and heavy crude oils (all types)	Tarry or waxy lumps.	Nonspreading, cannot be recovered from water surfaces using most conventional cleanup equipment, cannot be pumped without pre-heating or slurring, initially relatively nontoxic, may melt and flow when stranded in sun

TABLE 3 SHORELINE CLASSIFICATION (from Woodward-Clyde, 1979)

Substrate Type	Grain Size (mm)		General Descriptive Features
Mud	< 0.06	o	< 1° beach slope
		o	Develop in areas where there is a source of fine material
		o	Incised by a complex network of creeks and channels despite the generally flat surface
		o	Saturated with water; even at low tide, the mud deposits are usually covered with a thin film of water that cannot drain through the closely packed sediments
		o	Low bearing capacities frequently incapable of supporting the weight of a person
Sand	0.06-2.0	o	1° - 40° beach slope
		o	Subjected to seasonal erosion and deposition cycles as a consequence of the varying levels of incoming wave energy and to a lesser extent, ebb and flood tidal action
		o	Closely packed substrate with a low water infiltration rate
Gravel	2.0-50	o	Narrower and steeper beach slope than sand beaches
		o	Storm ridges
Cobble	50-256	o	Narrower and steeper beach-face than gravel beaches
		o	Rock fragments are somewhat rounded or modified by abrasion
		o	Storm ridge usually present
Boulder	<256	o	Detached rock masses that are somewhat rounded or otherwise distinctively shaped by abrasion in the course of transport
		o	Typically located near the base of cliffs or rocky outcrops; often found on pocket beaches

TABLE 3 SHORELINE CLASSIFICATION (Cont'd)

- |                            |  |
|----------------------------|--|
| <b>Rock Cliffs</b>         | <ul style="list-style-type: none"><li>o Typically associated with emergent coastlines</li><li>o Occur as a result of high relief in the coastal zone because the rocks or unconsolidated material are rapidly eroded by littoral processes</li><li>o Often little or no sediment accumulation at the cliff base allowing erosional processes to act directly on the cliffs</li></ul> |
| <b>Platforms</b>           | <ul style="list-style-type: none"><li>o Typically occur in shallow waters at the base of rock cliffs</li><li>o Sediment cover, if it occurs, does not provide a protective cover; wave- and tide-induced processes act directly on the rock surfaces</li></ul>   |
| <b>Man-Made Structures</b> | <ul style="list-style-type: none"><li>o Any structure found on a shoreline constructed or fabricated by man</li><li>o Examples include piers, boat ramps, seawalls, groins, rock jetties, oil handling facilities, houses, etc.</li></ul>  |
-

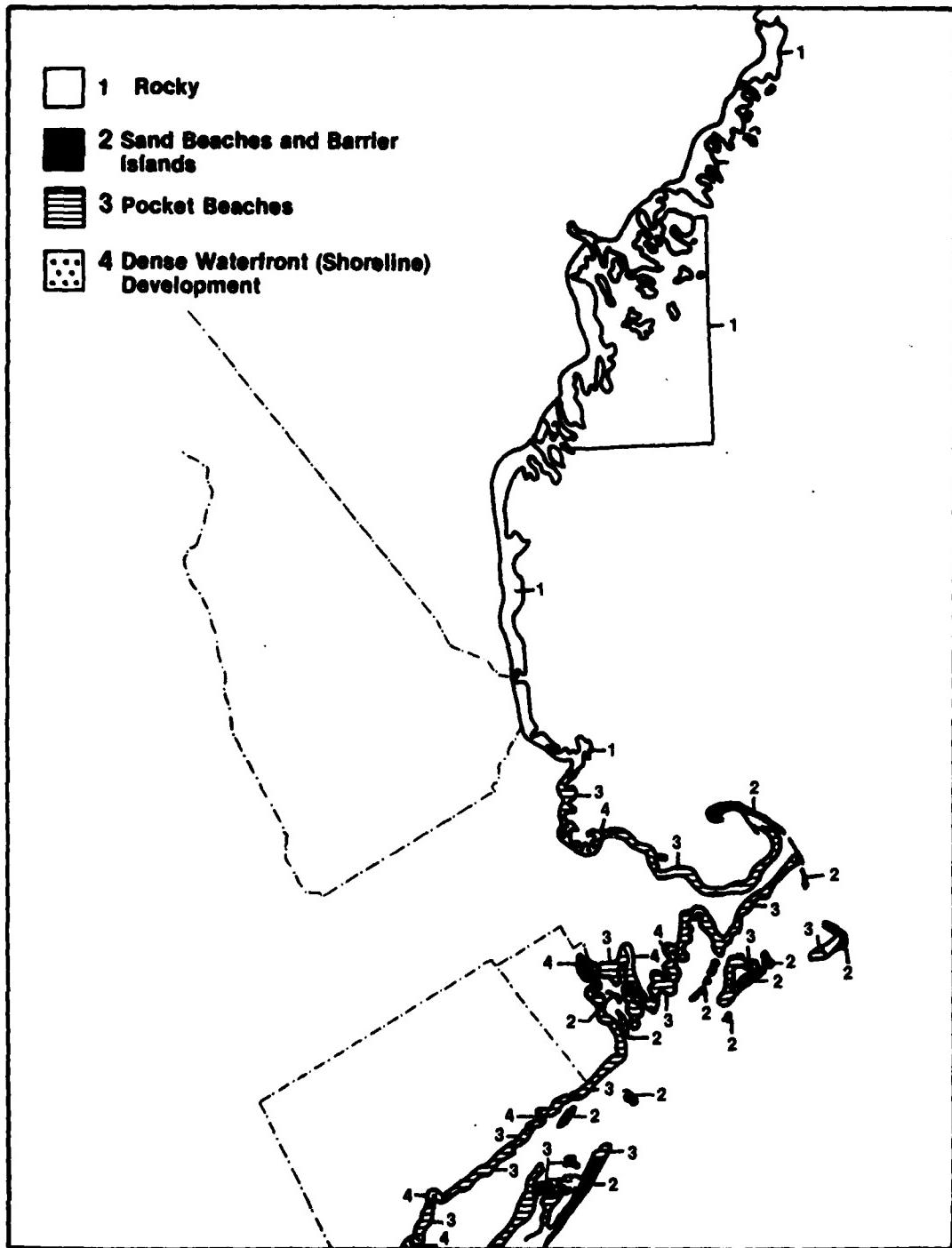


Figure 6.--Shoreline characteristics, Gulf of Maine coastline.

Three rules of thumb for oil persistence follow:

(1) The deeper the oil penetrates into the substrate, the longer is its persistence. Oil beneath the surface is protected from solar radiation and mechanical energy. Oil is buried rapidly in areas of high sedimentation.

(2) The lower the substrates energy level, the longer the oil will remain. Greater wave action, leads to greater mechanical energy, which serves to degrade and weather the oil. Other processes such as photo-oxidation, biodegradation, dissolution, evaporation, and emulsification are also related to energy level.

(3) The colder the air and water temperatures, the longer the oil persists. Decreasing temperatures lead to decreasing physical and biological (microbial) degradation rates.

It should be noted that oil can have secondary effects on adjacent shorelines. Once oil reaches a specific beach region it can be washed back out to sea and deposited elsewhere, creating further damage.

#### 2.14 General Environmental Considerations for Oil Mitigation

Apart from the indirect effect of environmental conditions which cause spreading, weathering and emulsification, meteorological and oceanographic conditions directly influence the ability to take countermeasures against oil spills. Environmental conditions such as wind, visibility, and waves influence at-sea operations for ships and aircraft. The choice of countermeasures will be thus influenced by these conditions.

Several oil mitigation techniques exist. Devices such as mechanical booms (that act as barriers to trap the oil), chemical barriers (that confine oil slicks), spray dispersants, sinking devices, oil burning, and pumps and filters aid in oil cleanup. All of these depend upon the environmental factors acting on the oil spill.

The following sections give a brief description of mitigation techniques and certain environmental restrictions.

##### 2.14.1 Mechanical booms

Currents and wave height are important factors determining the efficiency of booms. Most authors agree that the types of booms with which there is sufficient experience fail at current speeds of 0.5 to 1.0 m/s or even less. At these speeds, oil droplets are carried with the water underneath the boom. Failure occurs above a wave height-wave length ratio of about 0.08.

#### 2.14.2 Pneumatic booms

These devices may be effective with current speeds up to 0.3 m/s. In the presence of short waves breaking at the pneumatic barrier, failure occurs at lower current speeds than in calm conditions; long waves can pass without disturbing the functioning of the boom.

#### 2.14.3 Chemical barriers

It can be expected that the mono-molecular layers used to confine oil slicks will be less effective in the case of strong winds. Furthermore, sea conditions may hinder the application from ships and perhaps also from aircraft.

#### 2.14.4 Spraying with dispersants

Spraying equipment aboard ships usually can be operated only if the sea is not too rough. On the other hand, some agitation of the surface water is favorable for dispersion.

#### 2.14.5 Oil sinking

Weather conditions, and possibly chemical dispersants, may influence oil sinking. To determine the feasibility of this method, information on the region's bottom currents is necessary.

#### 2.14.6 Burning oil

Fire risks and the possibility of air pollution require real-time meteorological information (atmospheric stability, wind speed and direction) before this approach is considered.

### 2.15 Oil Spill Modeling

Oil spill models can be useful for oil spill contingency planning and real time mitigation. Knowledge of the movement of a surface oil slick is important in warning of possible shoreline pollution and in application of cleanup countermeasures. Oil spill modeling techniques have been developed to predict the movement of an oil spill under actual or hypothetical conditions.

Generally, oil spill models have evolved into two groups:

Type I models: Multiple trajectory models for long-term strategic forecasts based on archived climatological data, and

Type II models: Single event models for specific day-to-day tactical forecasts, usually based on up-to-date real-time data.

Type I models are probabilistic in nature. The spill is hypothetical and the model is used primarily for environmental assessment for planning purposes. These models make use of a climatological representation of both the ocean currents and an added drift induced by local wind. Ocean currents are represented on a grid, while wind drift components, for which far greater amount of usable data are available, are treated as a time series. Tidal motions may be incorporated in nearshore and embayment areas where they may be deemed to contribute to advective transport.

Type I models treat advection only on the surface, and may incorporate potential impact targets such as spawning areas, fish migration routes, and areas of commercial fishing. All Type I models contain representations of shorelines as potential targets, but few Type I models explicitly include oil weathering algorithms. Type I models can be used to compute spill trajectories for real-time spills, provided their use is not intended to project in time and space beyond by local weather forecasts.

Type II models are deterministic in that the spill has occurred, or is expected to occur, in real time; thus, the driving forces acting on the spill are determined from real-time or forecastable parameters.

The success of Type II models depends on forecast wind speeds and directions. The advantages of working with Type II models include the high quality of output information concerning the spill in question. Disadvantages include the limited response time to incorporate the real-time data, and the large amount of input data required.

Several modeling techniques are found within these general model types. Some of the commonly used modeling techniques include:

- Oil fate models (Type II)
- Oil fate and effect models (Type I and Type II)
- Single event models (Type II)
- Climatological models (Type I)

#### 2.15.1 Oil Fate Models

The oil fate model is used to estimate the concentration, distribution, and residence time of various fractions of oil into various environmental sinks. An attempt is made to trace all the pathways that oil takes as it comes into contact with the biota. The resulting computer calculations include all known processes and parameters and their variable reaction rates. This approach is probably the most advanced scientifically, but, because of the detailed environmental data inputs required, has limited operational use.

#### 2.15.2 Oil Fate and Effect Models

The oil fate and effect model is similar to the fate model. It extends this type of calculation by using the output of a fate model as input to a biological effect model. It also requires detailed environmental data but, in general, is less sophisticated in its physical and chemical parameters than the fate model. This is a useful research tool but to date is also not considered to be an operational tool that can be used under actual spill conditions.

#### 2.15.3 Single Event Models

The single event model is probably the best tool decision makers have at their disposal for an actual spill, provided that the appropriate environmental data is available to the modeling support group. This model type generally attempts to incorporate the most important physical processes such as advection, diffusion, and spreading. It attempts to calculate future locations of oil based on input parameters such as wind conditions and the ambient current patterns, but it is limited by data inputs; and thus calculated trajectories are only as accurate as the sometimes unavailable inputs.

#### 2.15.4 Climatological Models

The climatological modeling technique is based on archived environmental data. It uses first-order calculations of currents to estimate oil advection. Usually advection is dominant over other environmental factors, and thus results have been useful in such spills as that of the Argo Merchant. The "permanent" current (derived from available atlas presentations) and a transient wind-driven current (derived from local wind records using the 3 percent rule; see section 3.1) are added to produce a trajectory. The trajectory is tracked in 3-hour intervals using a computer simulation from the hypothetical spill site. Additional trajectories are traced until relative risk diagrams can be drawn that indicate the major direction of oil movement and its variability. The advantage of this calculation is that it can be done before the spill occurs and kept available in a planning guide for a specific location. The disadvantage is that under actual conditions the model is only as reliable as the simple model assumptions. Also, using type of model for real-time forecast is limited by the assumption that conditions at spill time are close to the climatological mean. This approximation may be valid if the distance to an impact point is large.

In section 3.10, relative risk diagrams are presented for the Gulf of Maine/Georges Bank region using a climatological computer simulation, as explained in Bishop (1976). One can estimate the relative risk of various regions to impact by using the diagrams given the resource locations as explained in section 3.11.

### 3. ENVIRONMENTAL DATA

#### 3.1 Surface Wind Field

An oil spill at sea is influenced by weather conditions. Surface wind conditions produce wind waves and wind-driven currents. Wind waves mix the oil both into the water column and horizontally. Also, in theory, wave height is related to a downwind wave-driven current. Surface wind-driven currents, in theory, flow to the right of the wind. The combined oil advection due to waves and wind-drift has been observed to be about 3 percent of the wind's magnitude, directed within 15° to the right of the wind (in the Northern Hemisphere). Other meteorological factors, such as the movement and location of major weather systems and atmospheric fronts, are important because of shifting wind conditions associated with such disturbances.

The study region lies in a zone of prevailing westerly winds that dominate the northeastern United States. The weather patterns are influenced by several major atmospheric features, by major oceanographic features and, on a local level, by the interaction between the atmosphere and the ocean.

The two semi-permanent pressure centers that alternately dominate the region, the Icelagdic Low (approximately 63°N) and the Bermuda-Azores High (approximately 31°N), influence the pressure pattern and therefore the general air circulation. The alternating dominance of the Icelandic Low in the winter and the Bermuda-Azores High in the summer contributes to the varying weather patterns and storm tracks in the region. As the Icelandic Low develops during the winter, prevailing winds shift to the northwest and the eastern offshore region becomes a major area of cyclogenesis. Hurricanes are infrequently observed in late summer and early autumn. The prevailing pressure patterns in the northwest Atlantic are illustrated in Figure 7.

The polar front coincides with the jet stream, an upper-level thermal gradient separating air masses of polar and tropical origin. The front has a generally southwest to northeast orientation and is important for storm development and direction of movement (Figure 8). The seasonal movement of frontal locations leads to the seasonal march in the mean wind field (Figures 9-20).

The above diagrams concerning the mean wind can be interpreted in terms of oil spill trajectory estimates in the following manner. In regions that are far enough from the impact point (for example, outside one tidal excursion), the most probable impact would occur along the mean wind direction. This type of climatological projection, based on wind-driven currents, is most accurate during seasons of low variability and will be modified in the presence of the prevailing permanent current. The variability can be interpreted in the context of the spread of oil spill trajectories starting from a common point. The climatological presentation depicting wind variability is the wind rose. Figures 21 through 32 show surface wind roses for the study region in which spring and summer roses indicate more of this

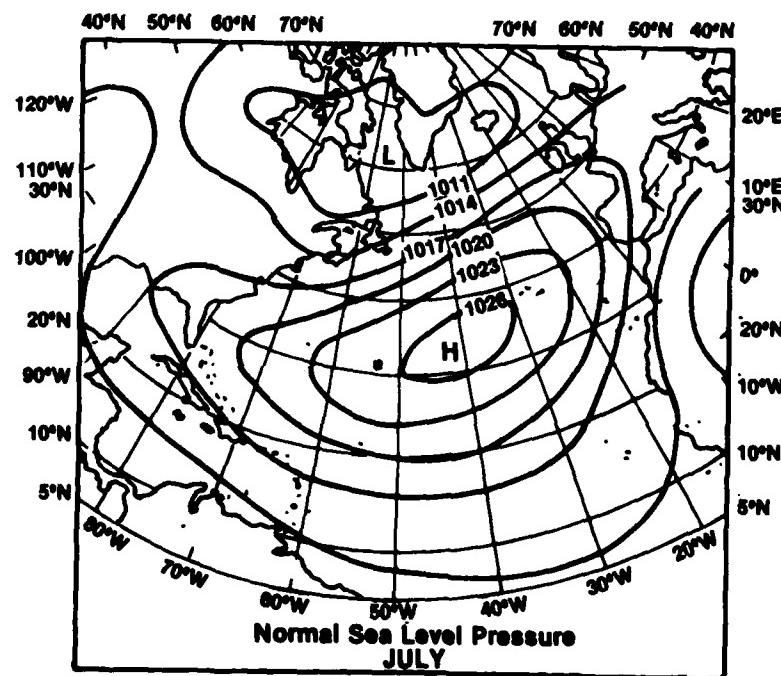
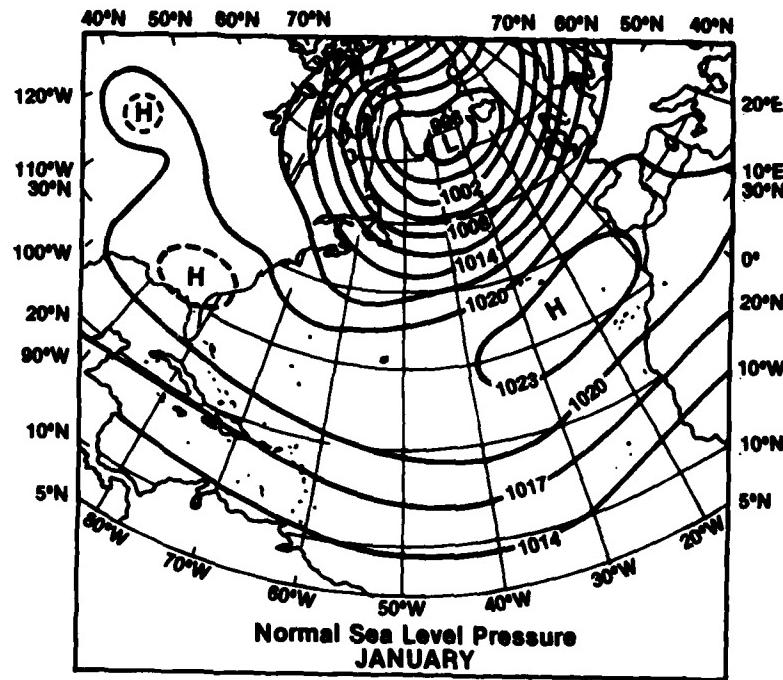


Figure 7.--Prevailing winter and summer pressure patterns in the North Atlantic (after Wright, 1976).

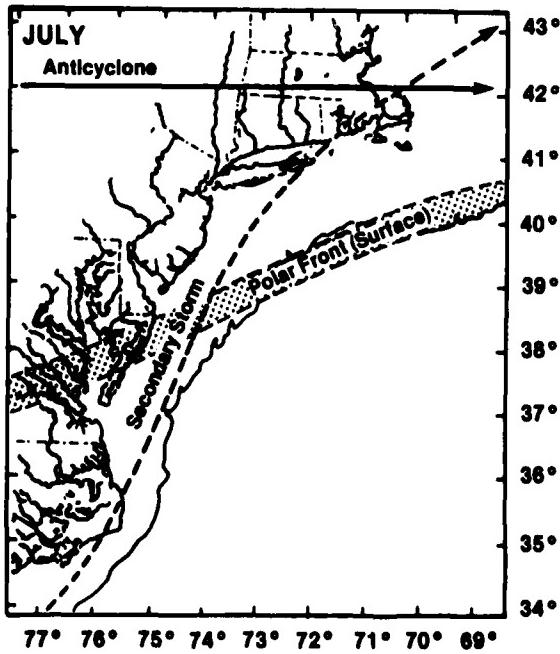
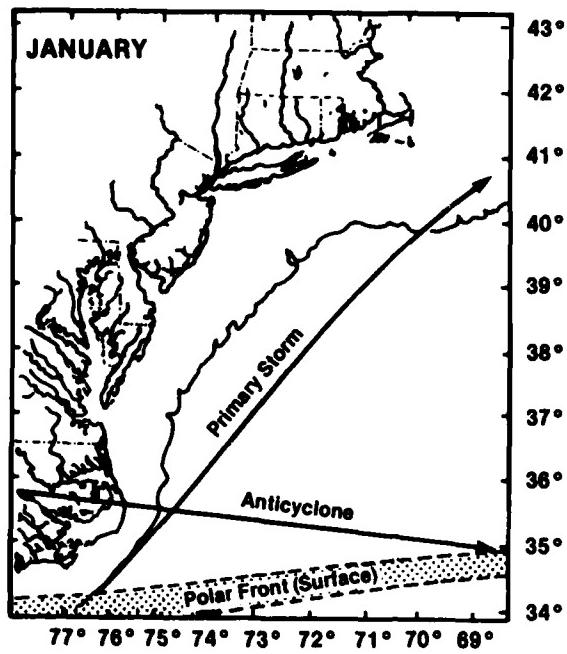


Figure 8.--Storm tracks, winter and summer (after Wright, 1976).

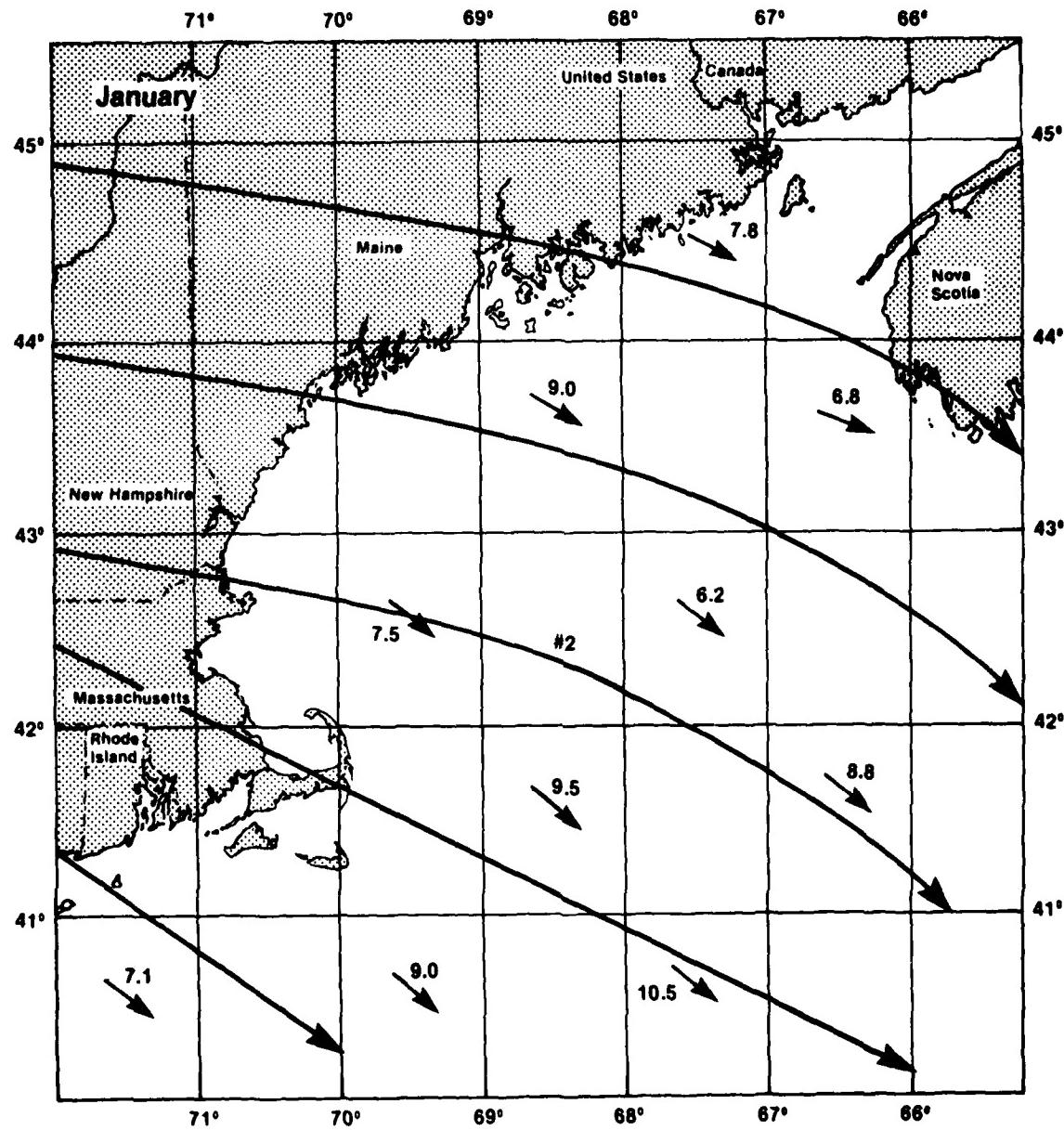
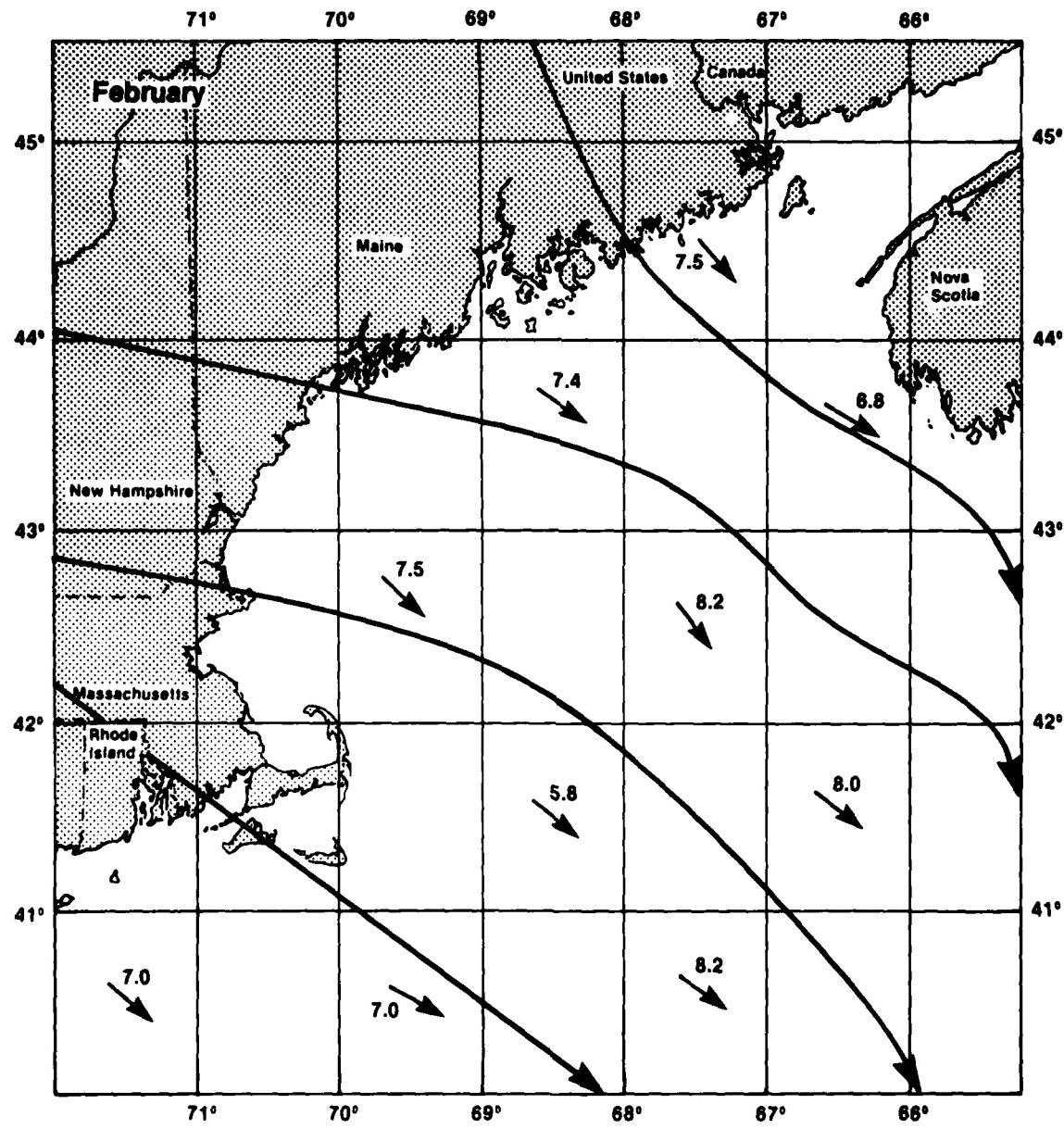


Figure 9.--January mean wind vectors in knots (after Godshall et. al., 1980).



**Figure 10.--February mean wind vectors in knots (after Godshall et. al., 1980).**

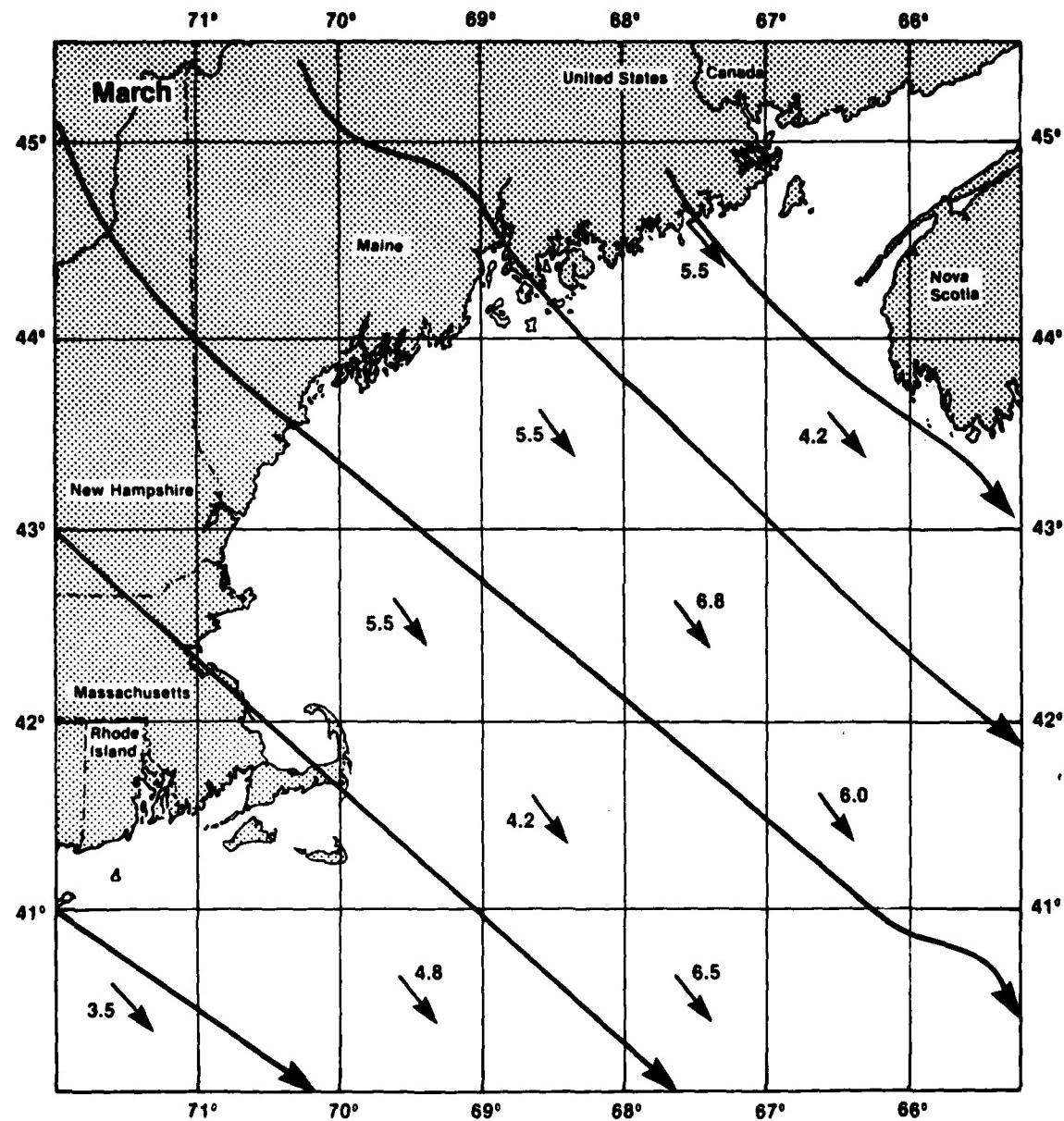
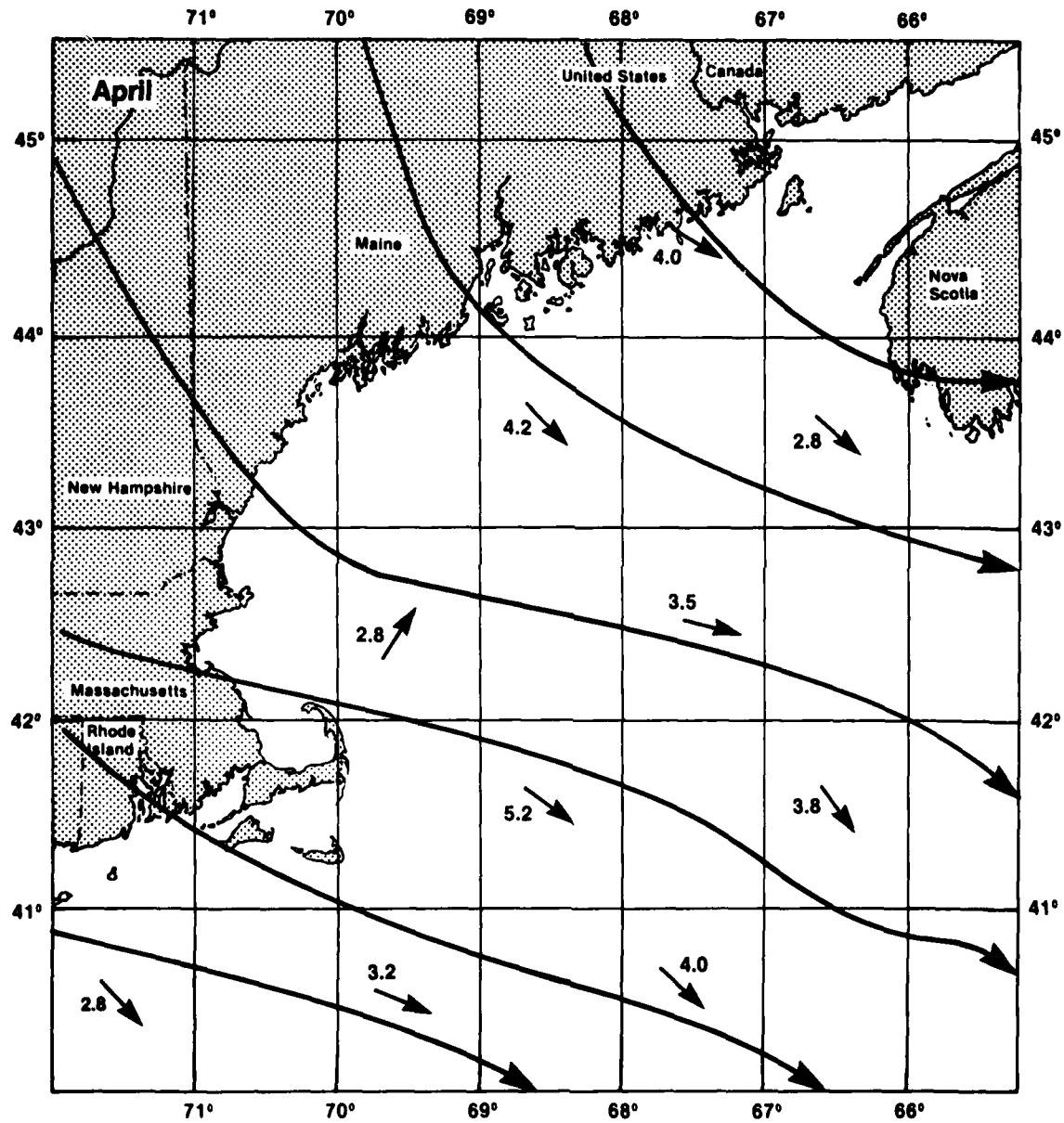


Figure 11.--March mean wind vectors in knots (after Godshall et. al., 1980).



**Figure 12.--April mean wind vectors in knots (after Godshall et. al., 1980).**

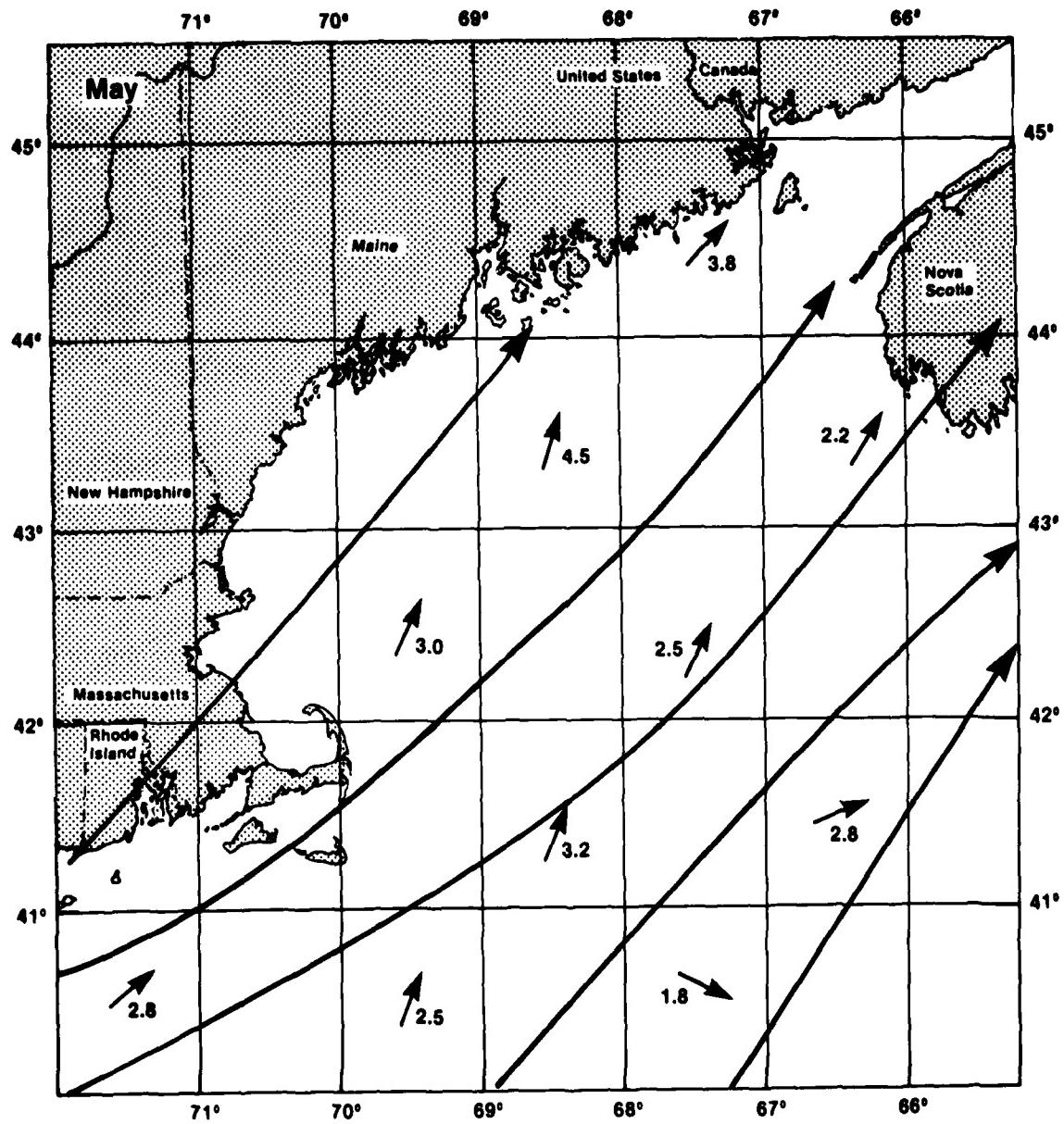


Figure 13.--May mean wind vectors in knots (after Godshall et. al., 1980).

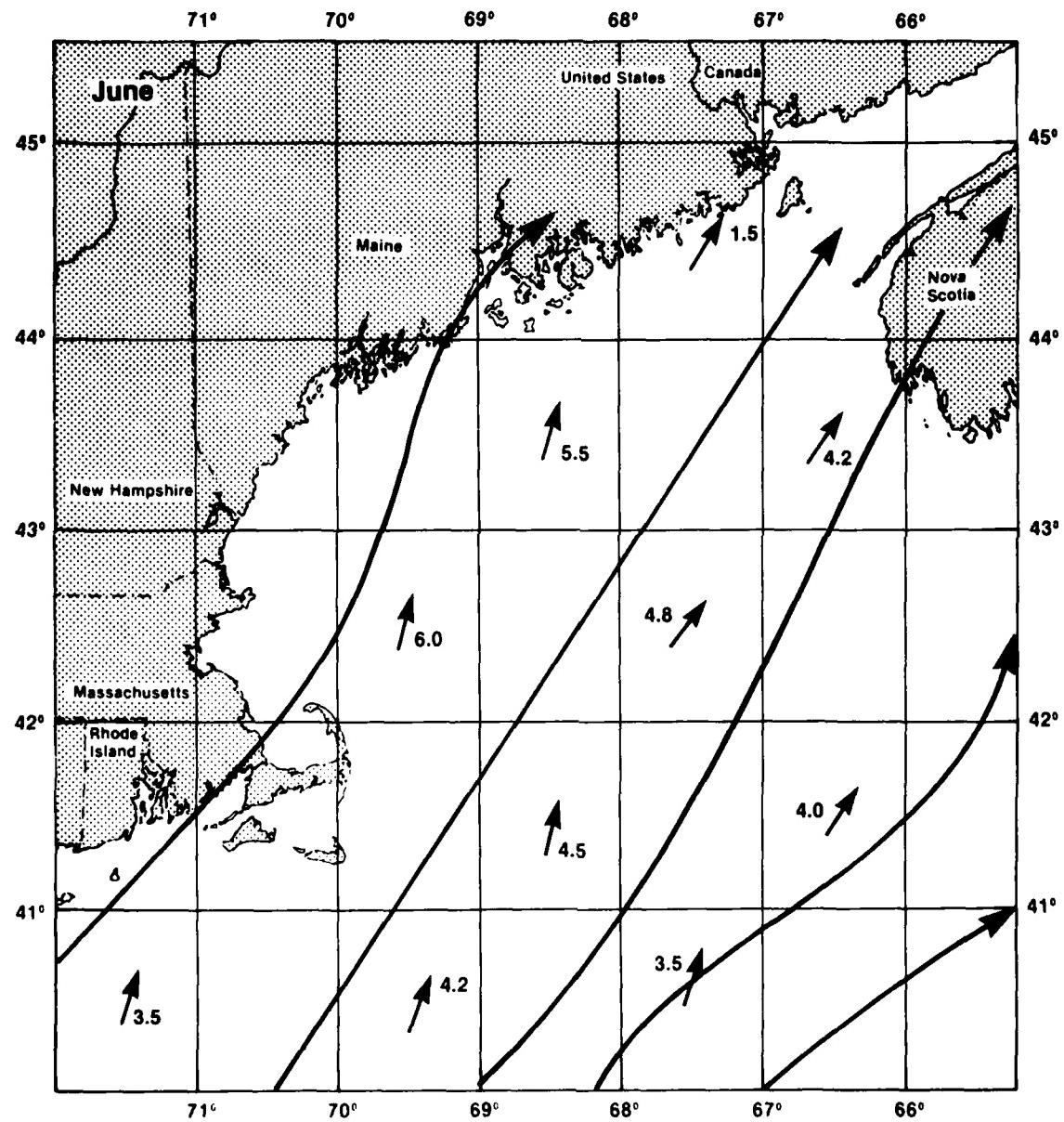
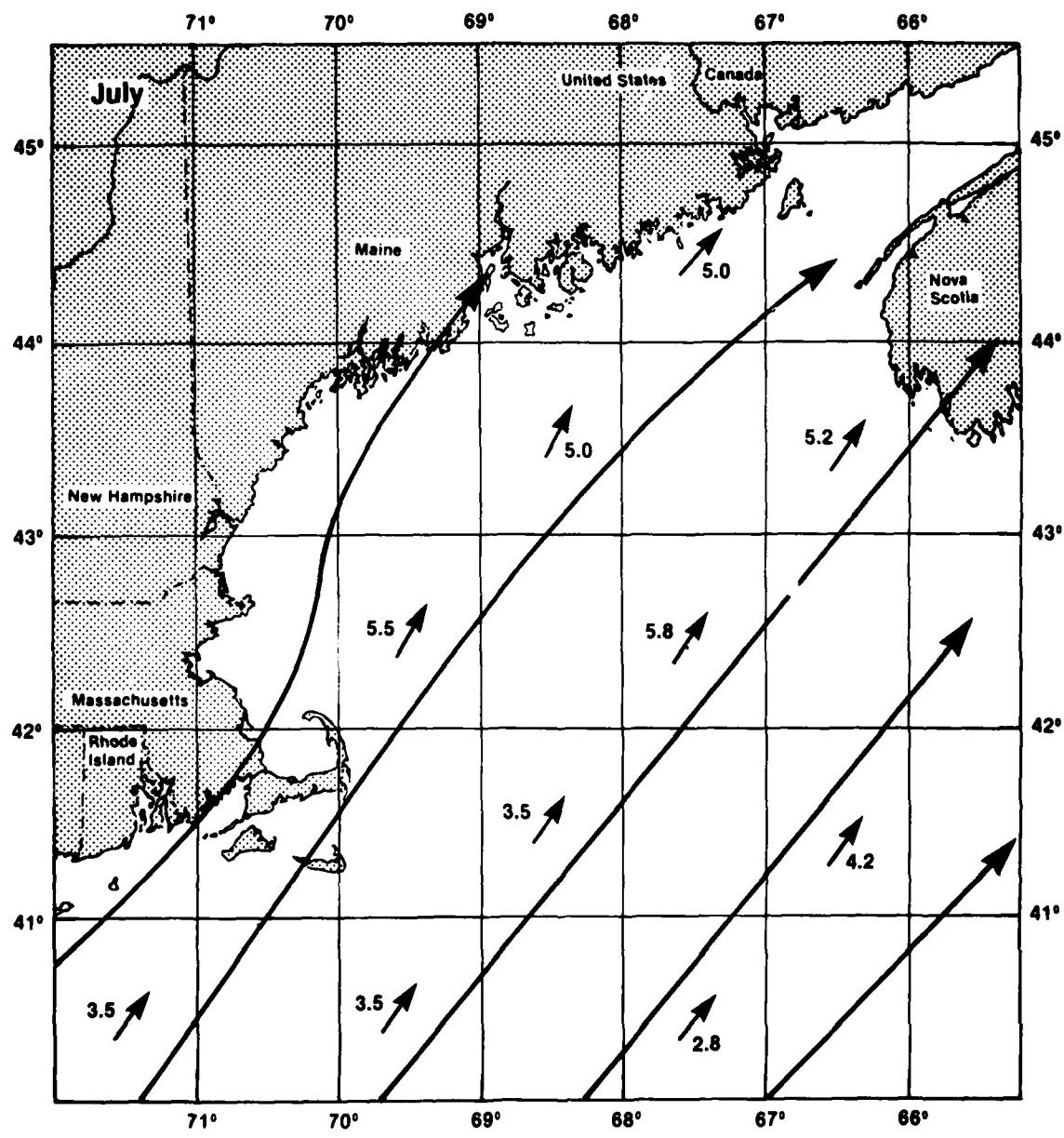


Figure 14.--June mean wind vectors in knots (after Godshall et. al., 1980).



**Figure 15.--July mean wind vectors in knots (after Godshall et. al., 1980).**

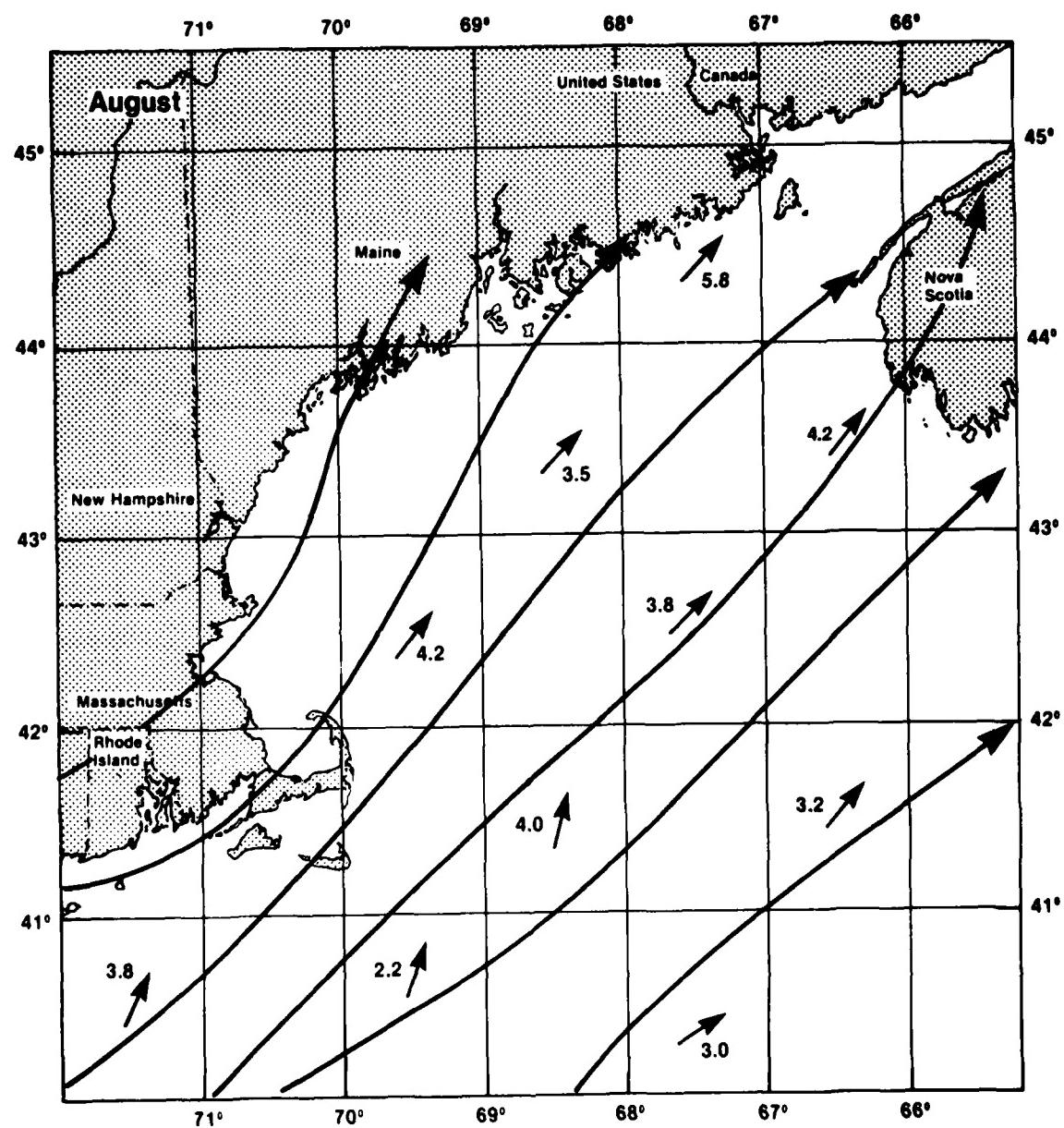
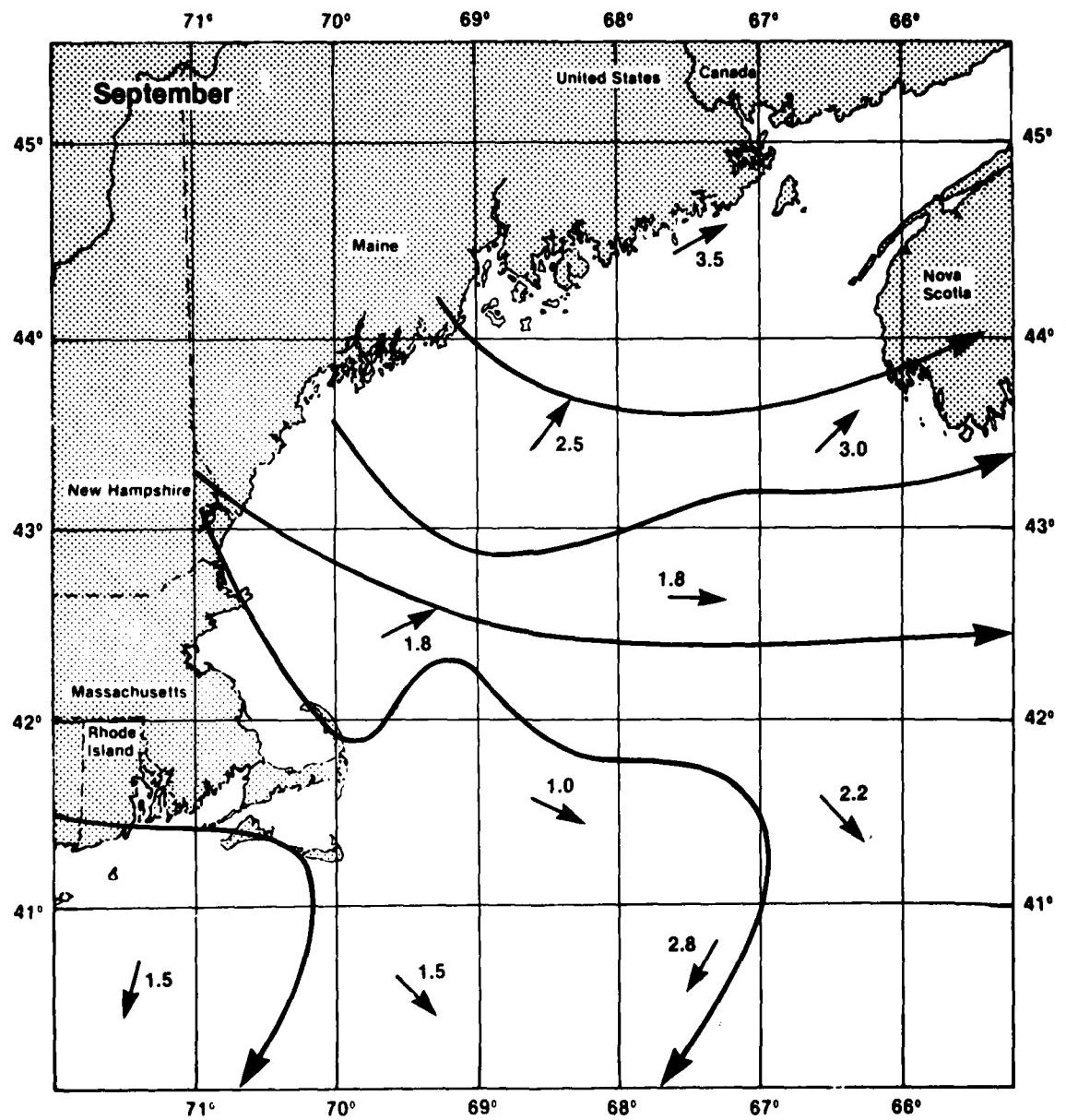


Figure 16.--August mean wind vectors in knots (after Godshall et. al., 1980).



**Figure 17.--September mean wind vectors in knots (after Godshall et. al., 1980).**

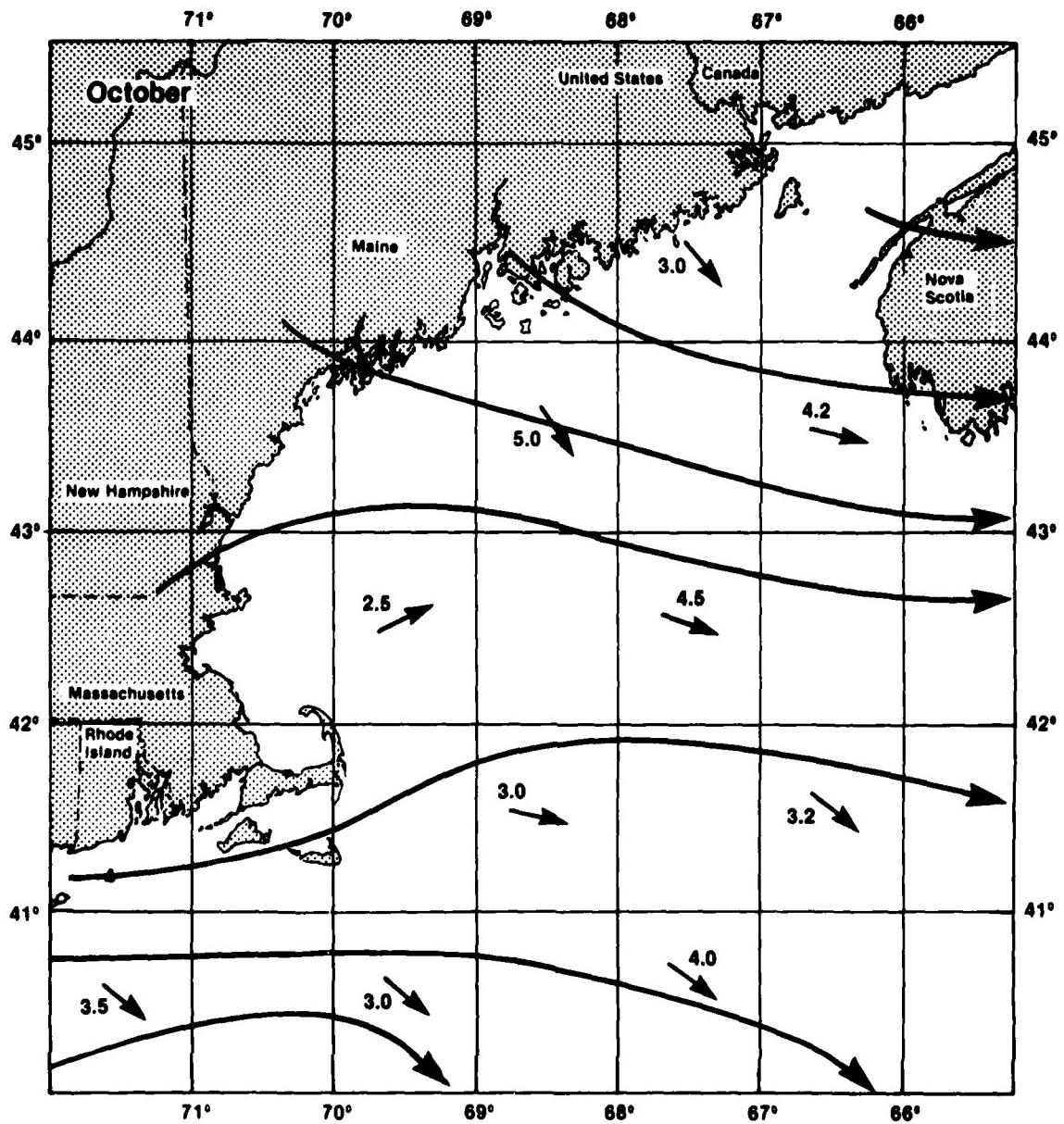


Figure 18.--October mean wind vectors in knots (after Godshall et. al., 1980).

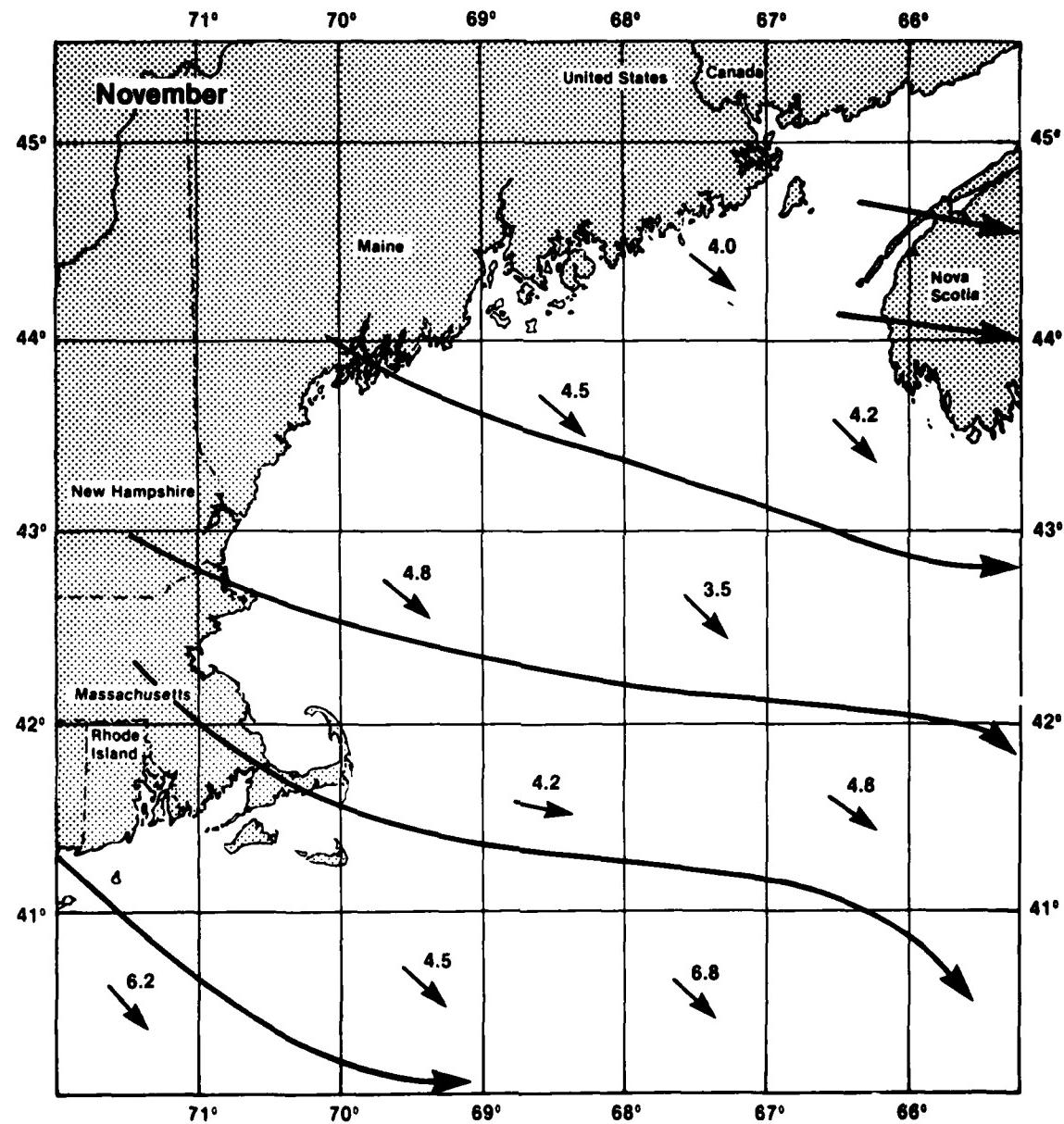
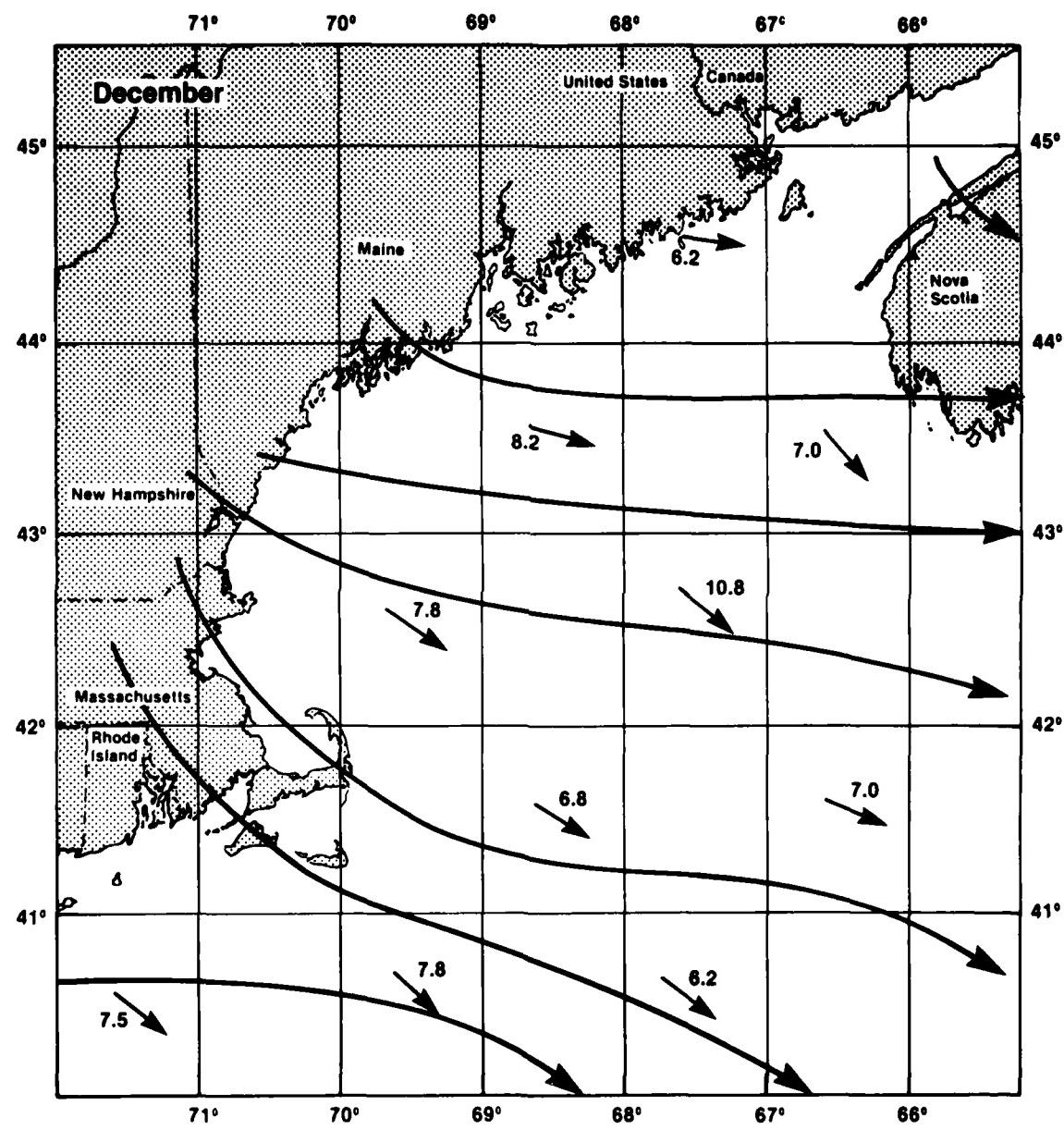


Figure 19.--November mean wind vectors in knots (after Godshall et. al., 1980).



**Figure 20.--December mean wind vectors in knots (after Godshall et. al., 1980).**

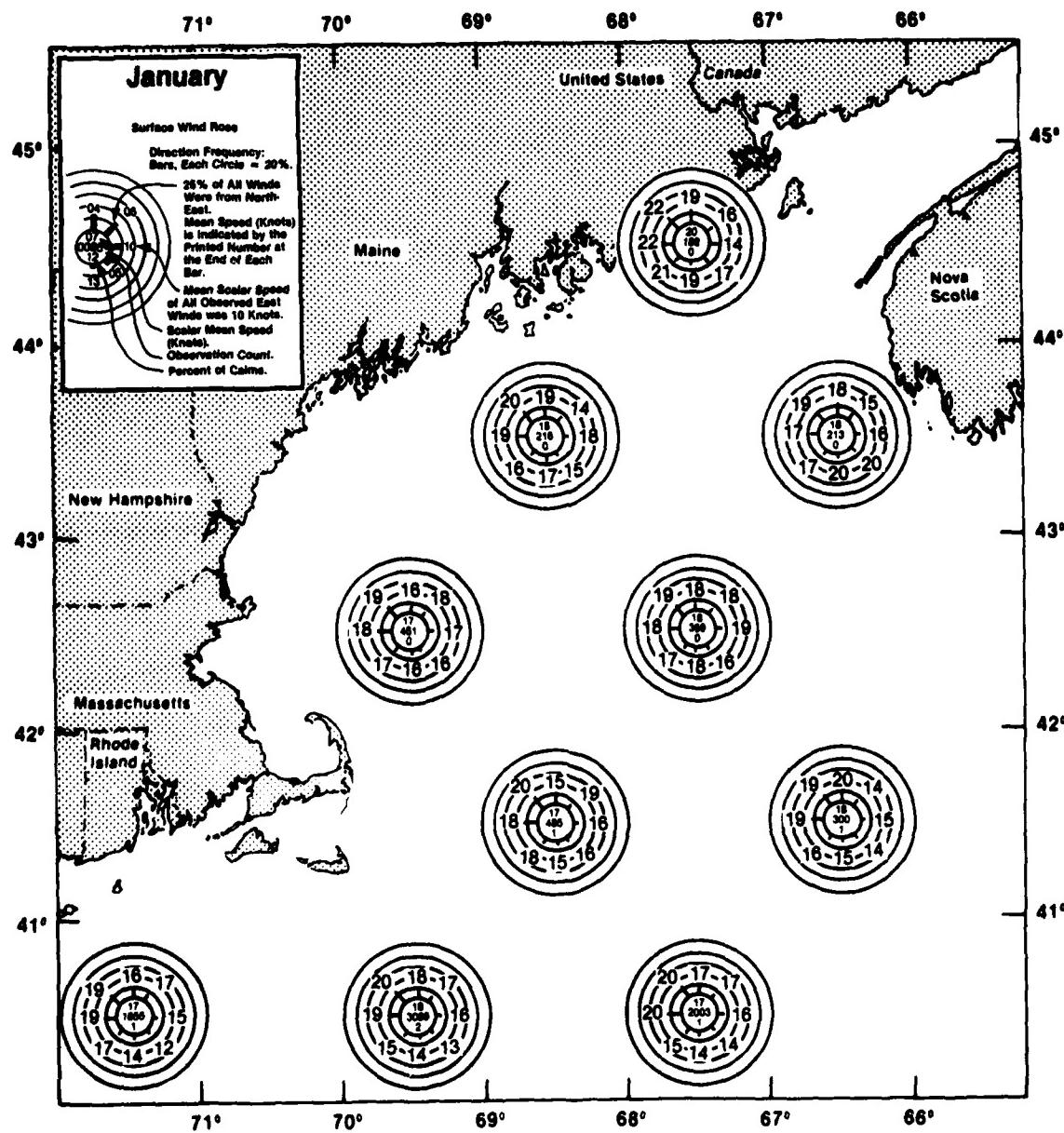
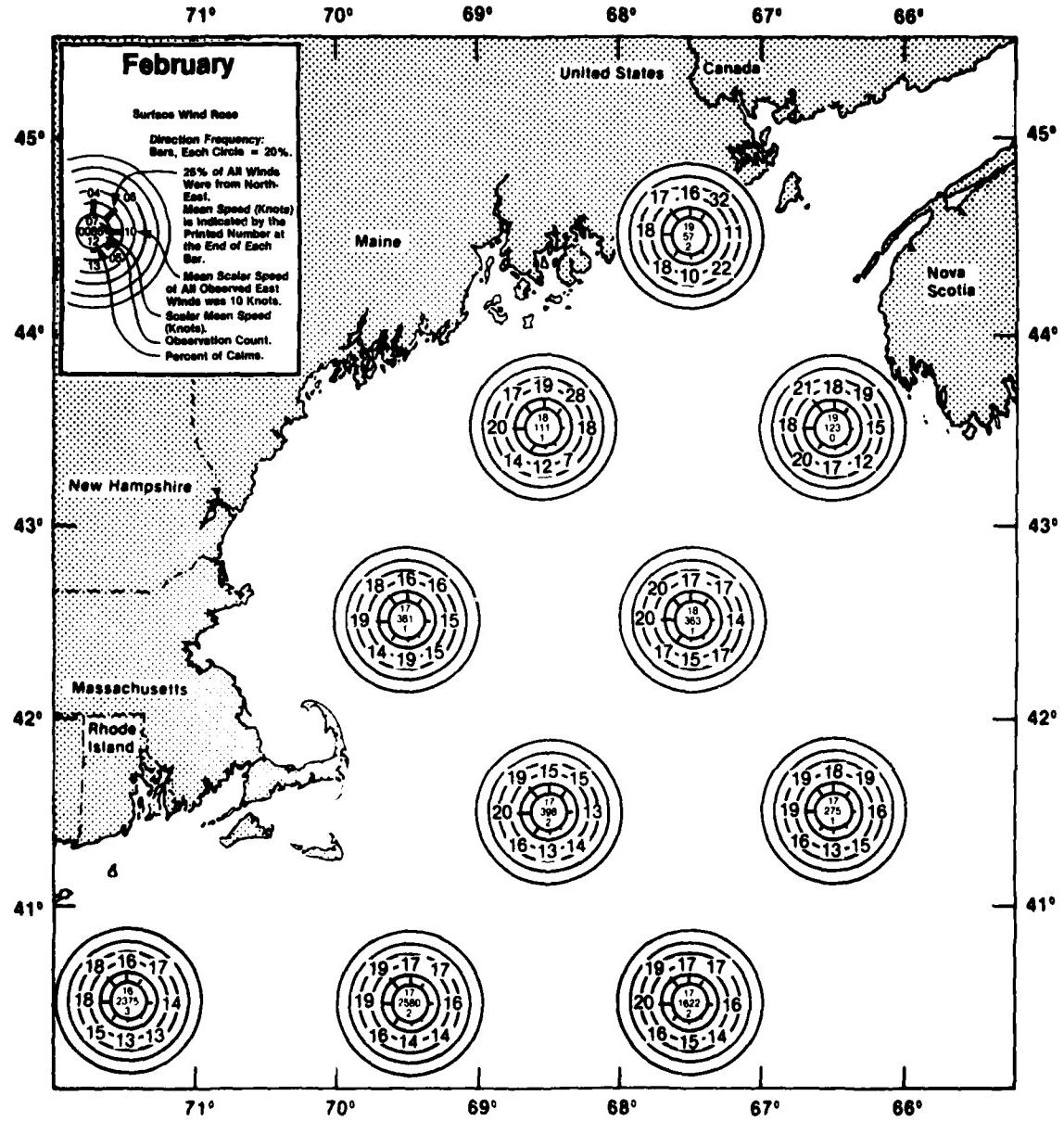


Figure 21.--January surface wind roses (after the National Weather Service, 1976).



**Figure 22.--February surface wind roses (after the National Weather Service, 1976).**

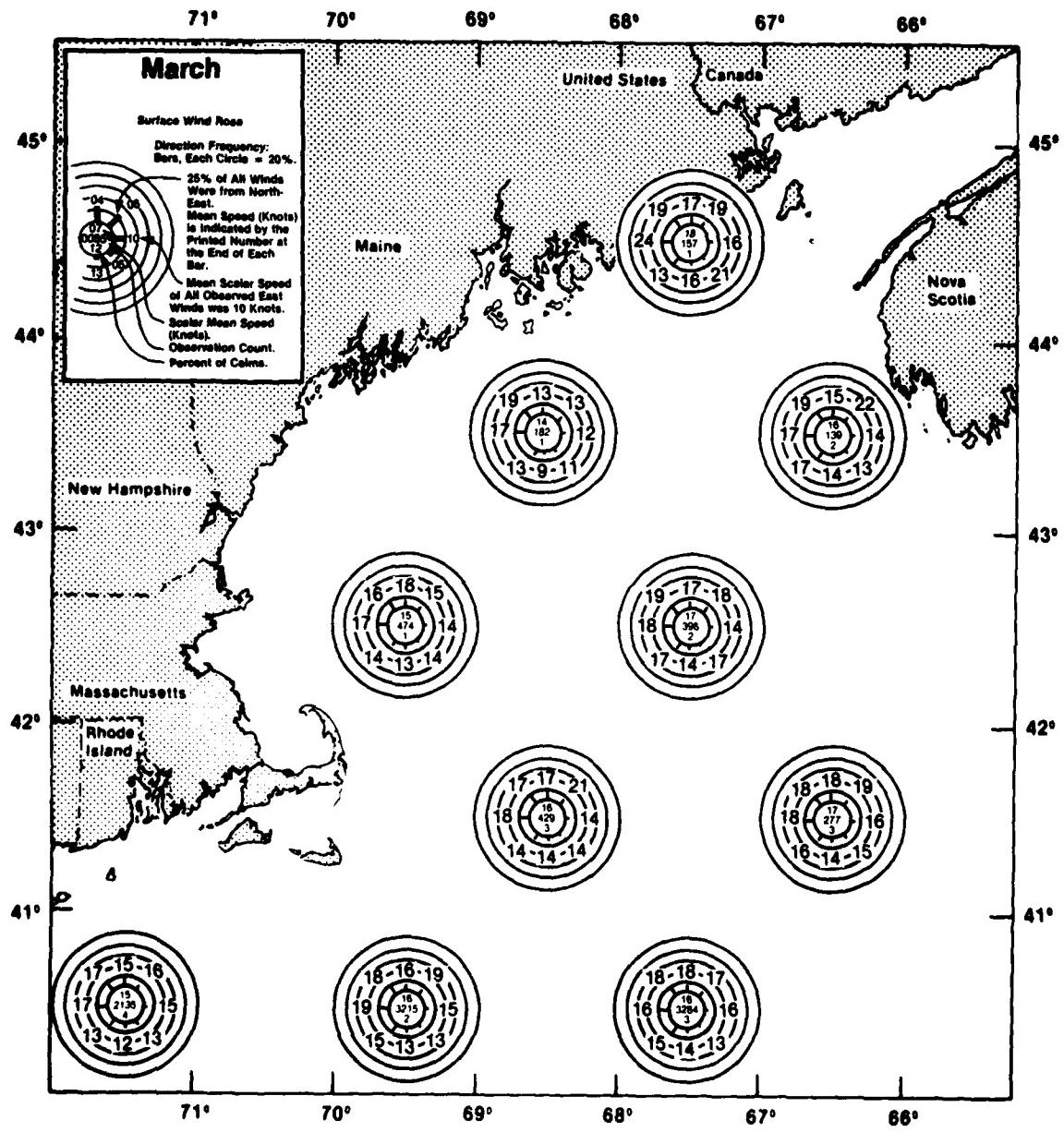


Figure 23.--March surface wind roses (after the National Weather Service, 1976).

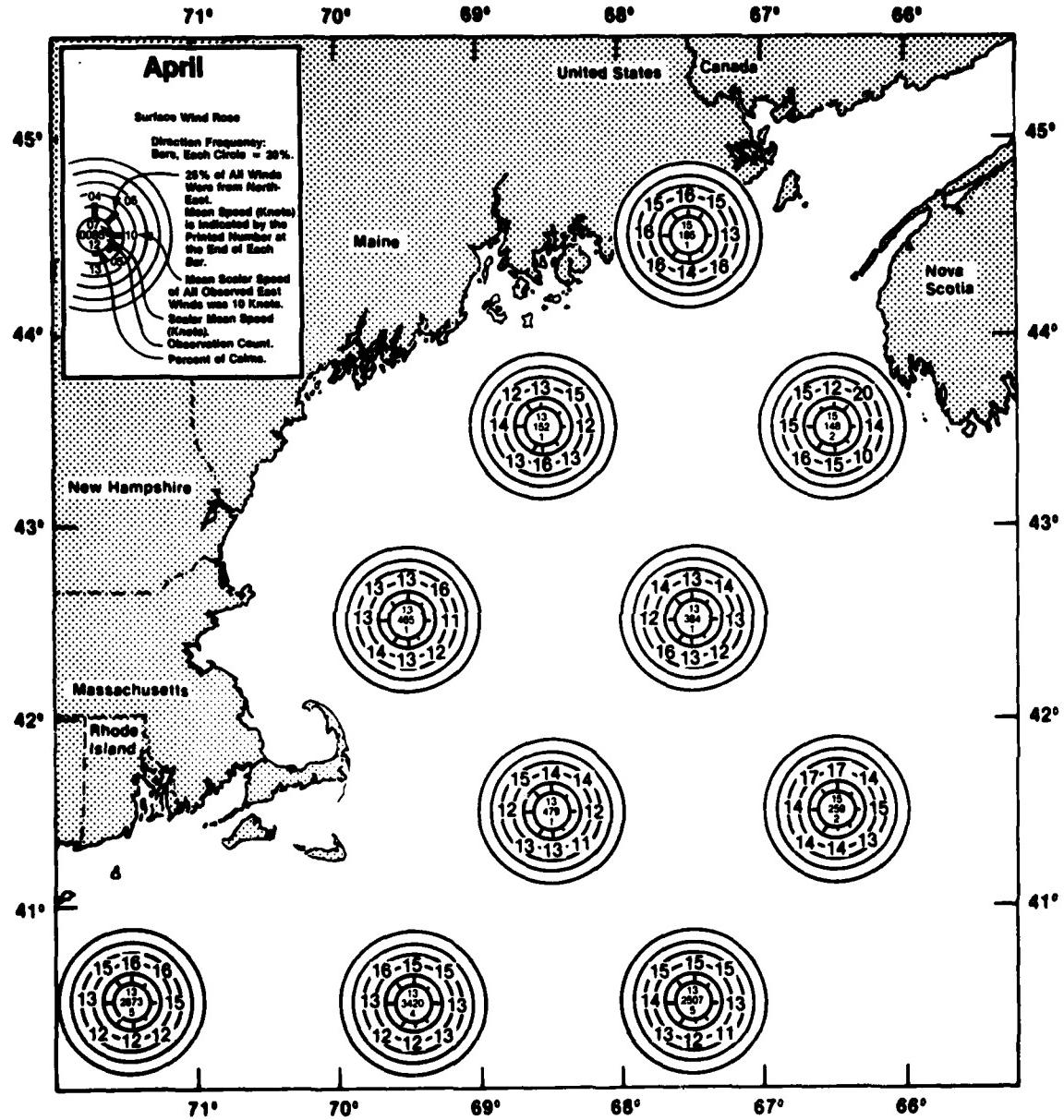


Figure 24.--April surface wind roses (after the National Weather Service, 1976).

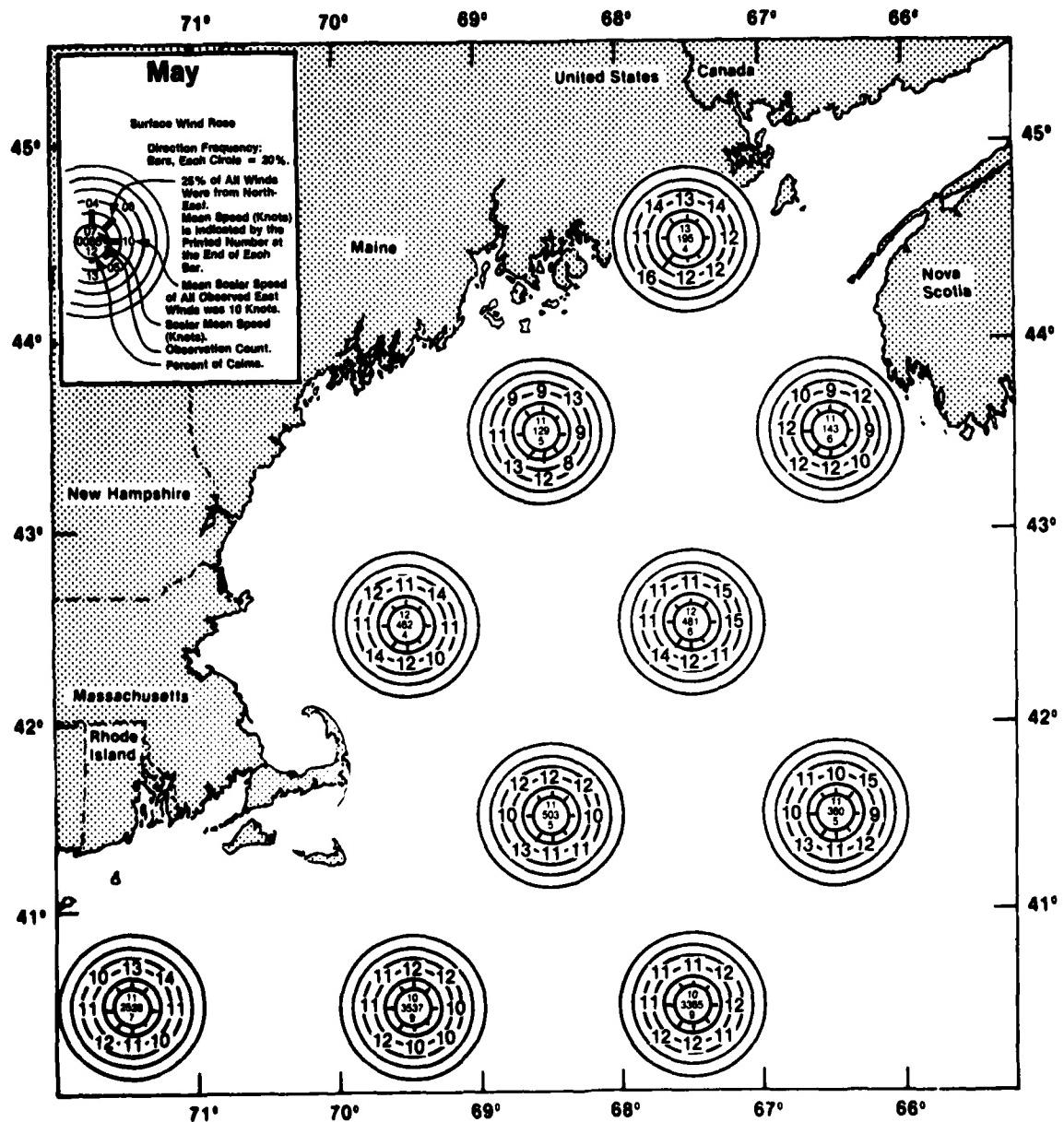


Figure 25.--May surface wind roses (after the National Weather Service, 1976).

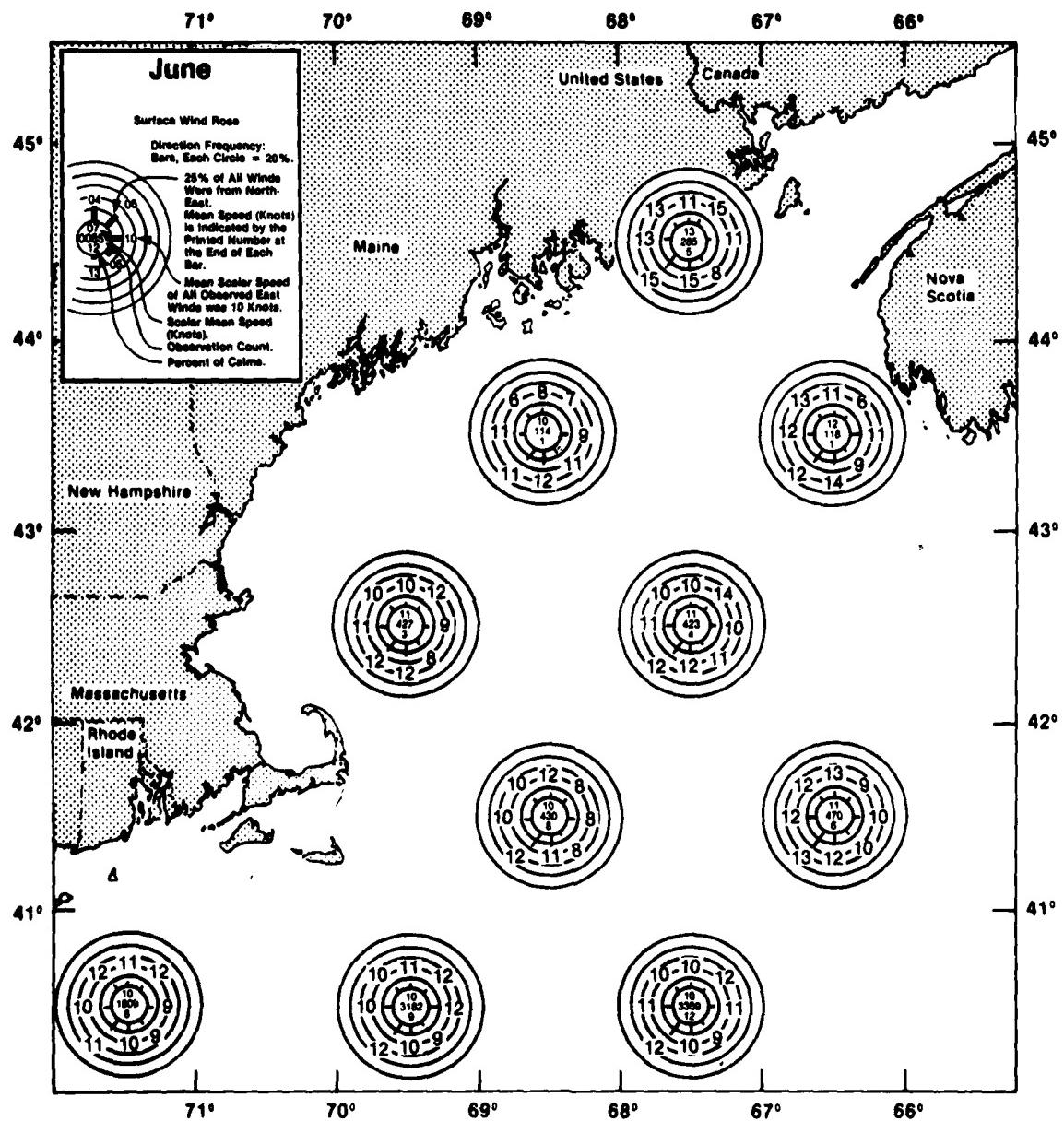


Figure 26.--June surface wind roses (after the National Weather Service, 1976).

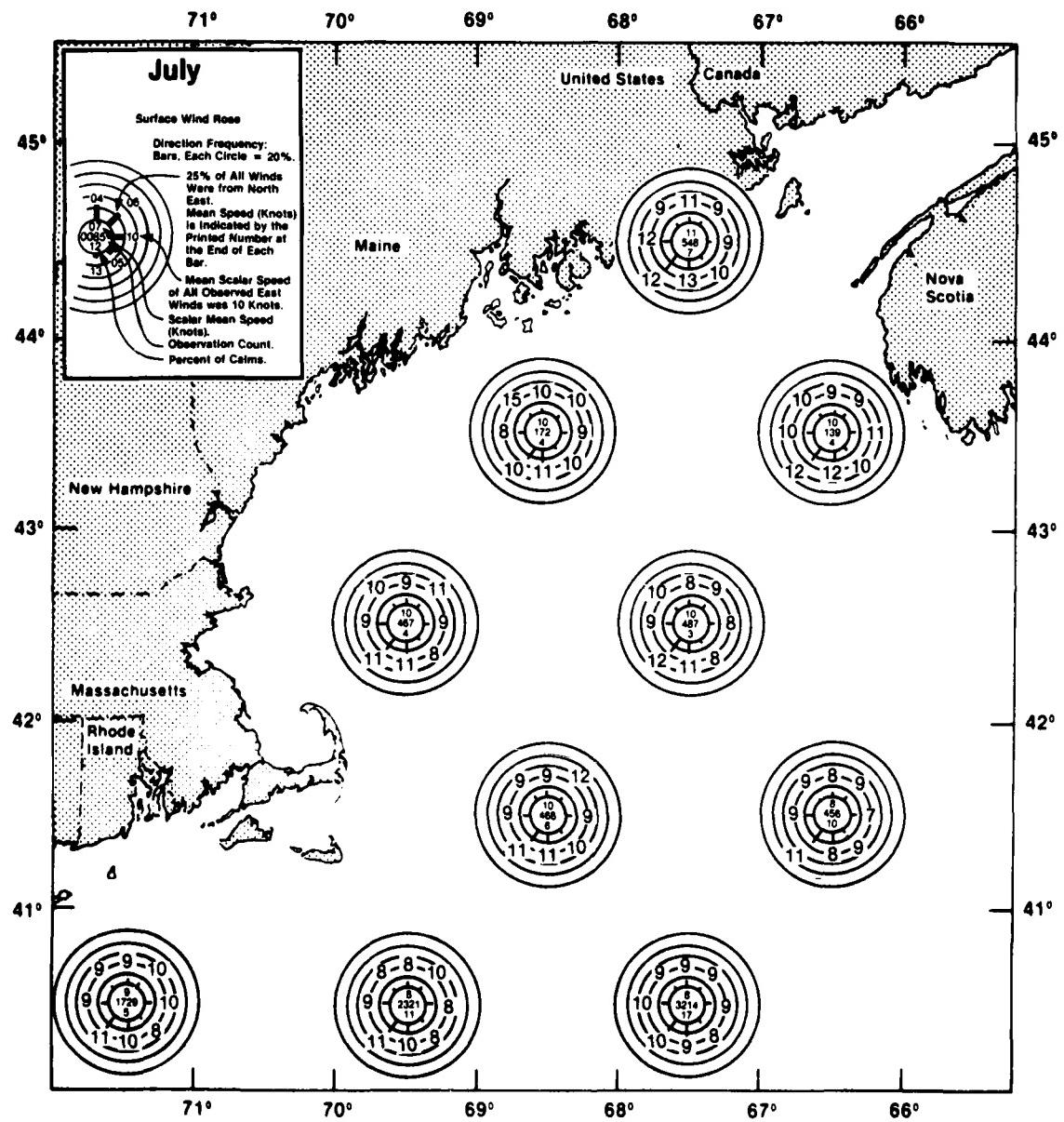


Figure 27.--July surface wind roses (after the National Weather Service, 1976).

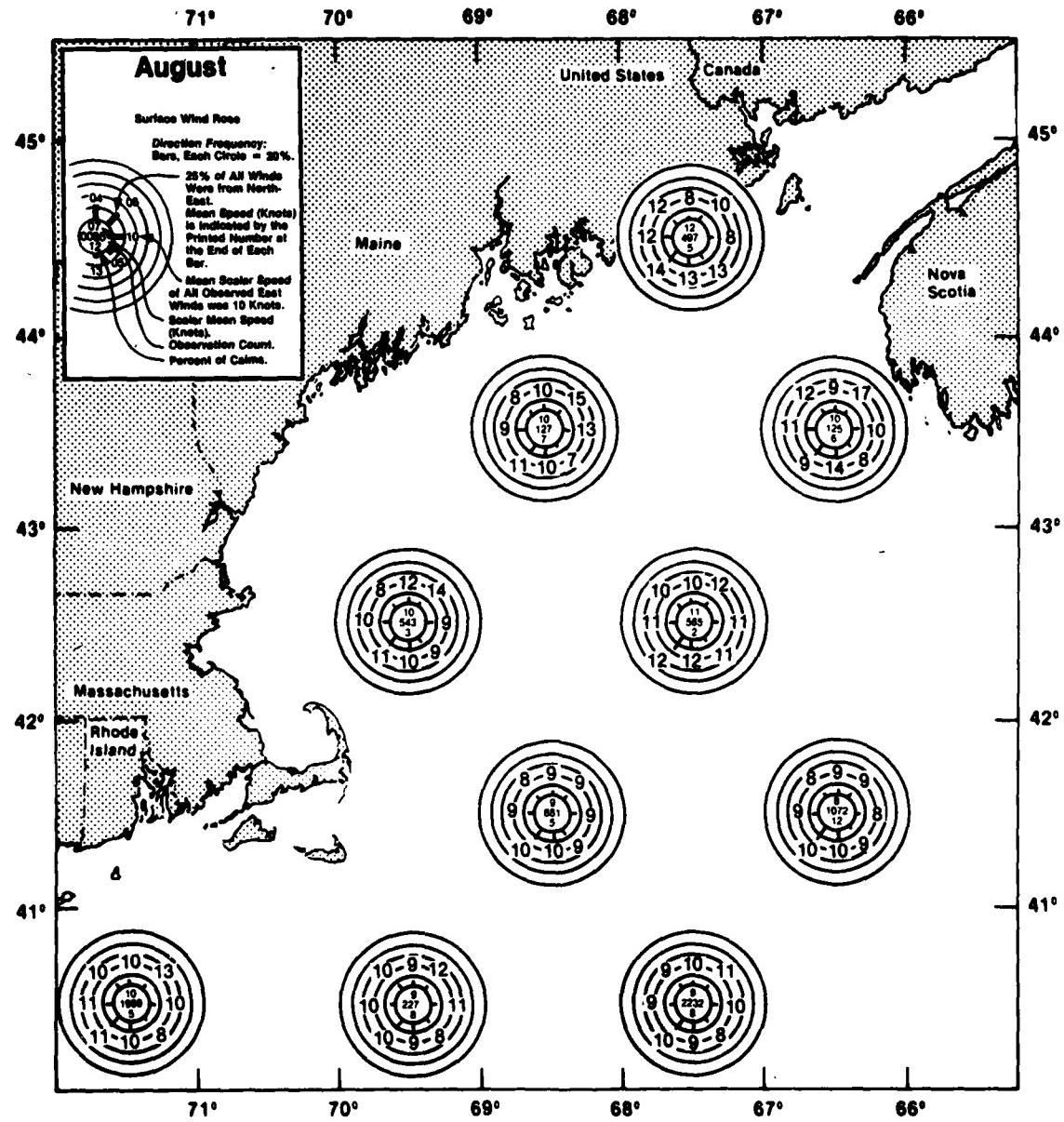


Figure 28.--August surface wind roses (after the National Weather Service, 1976).

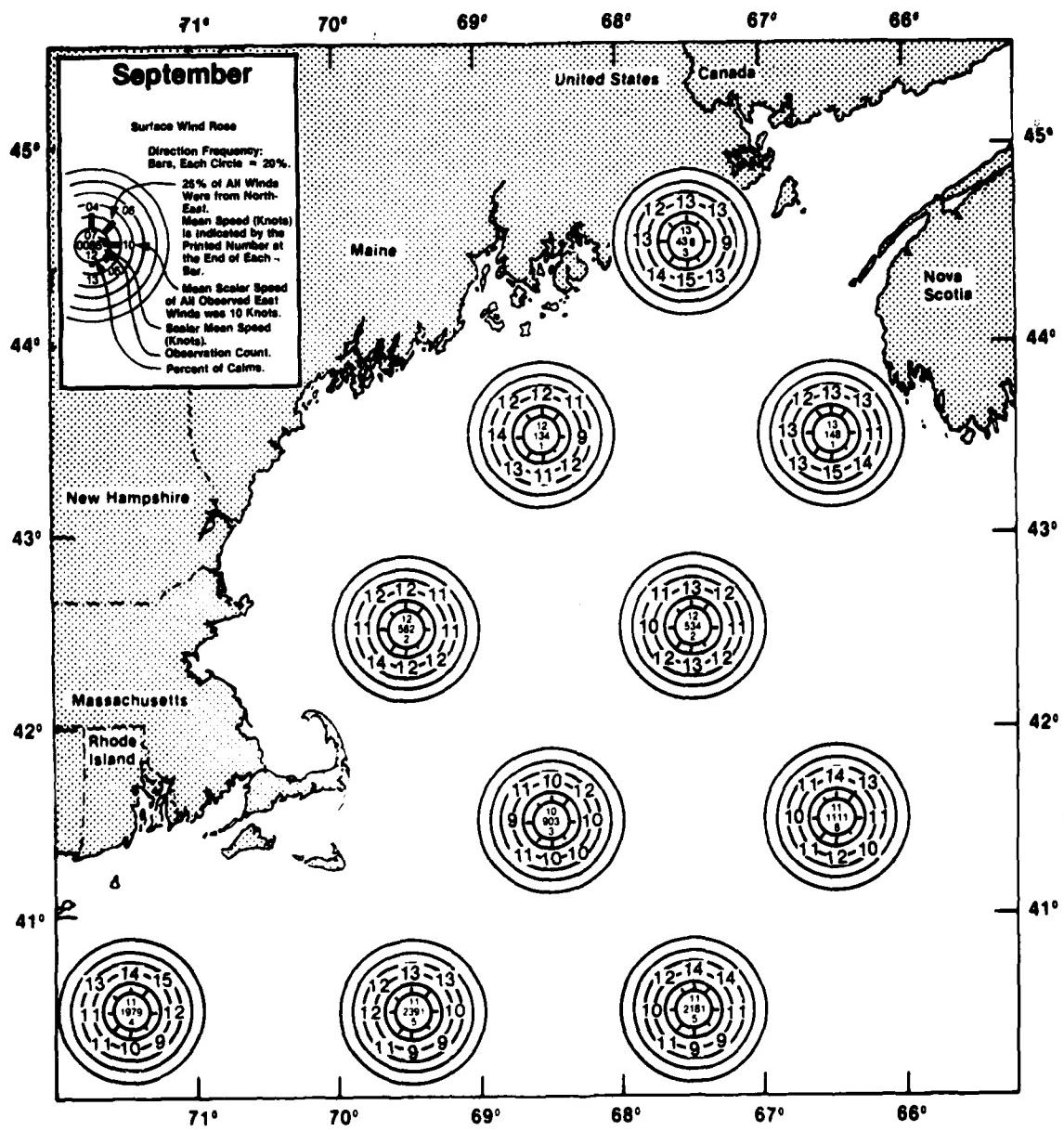


Figure 29.--September surface wind roses (after the National Weather Service, 1976).

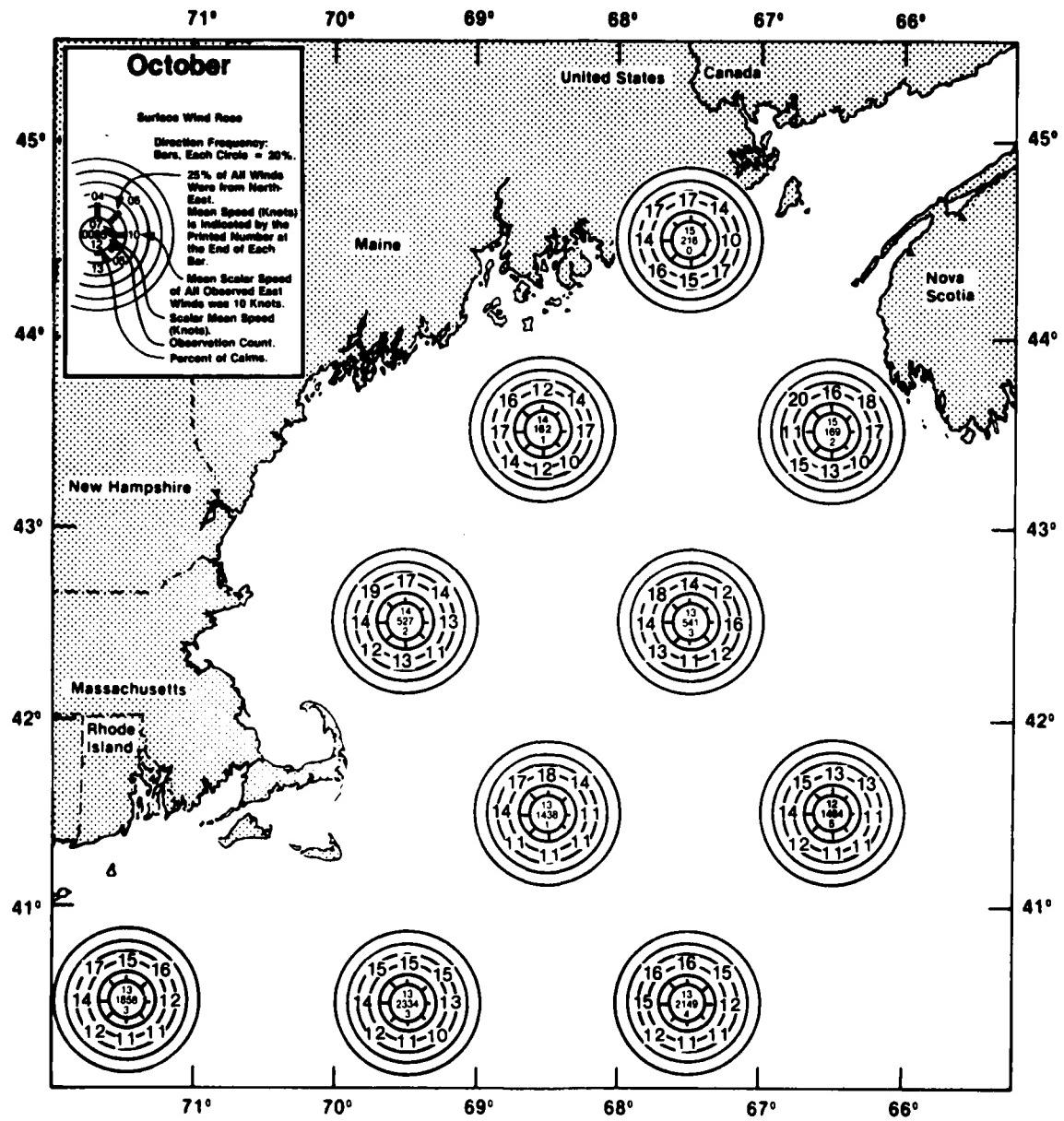


Figure 30.--October surface wind roses (after the National Weather Service, 1976).

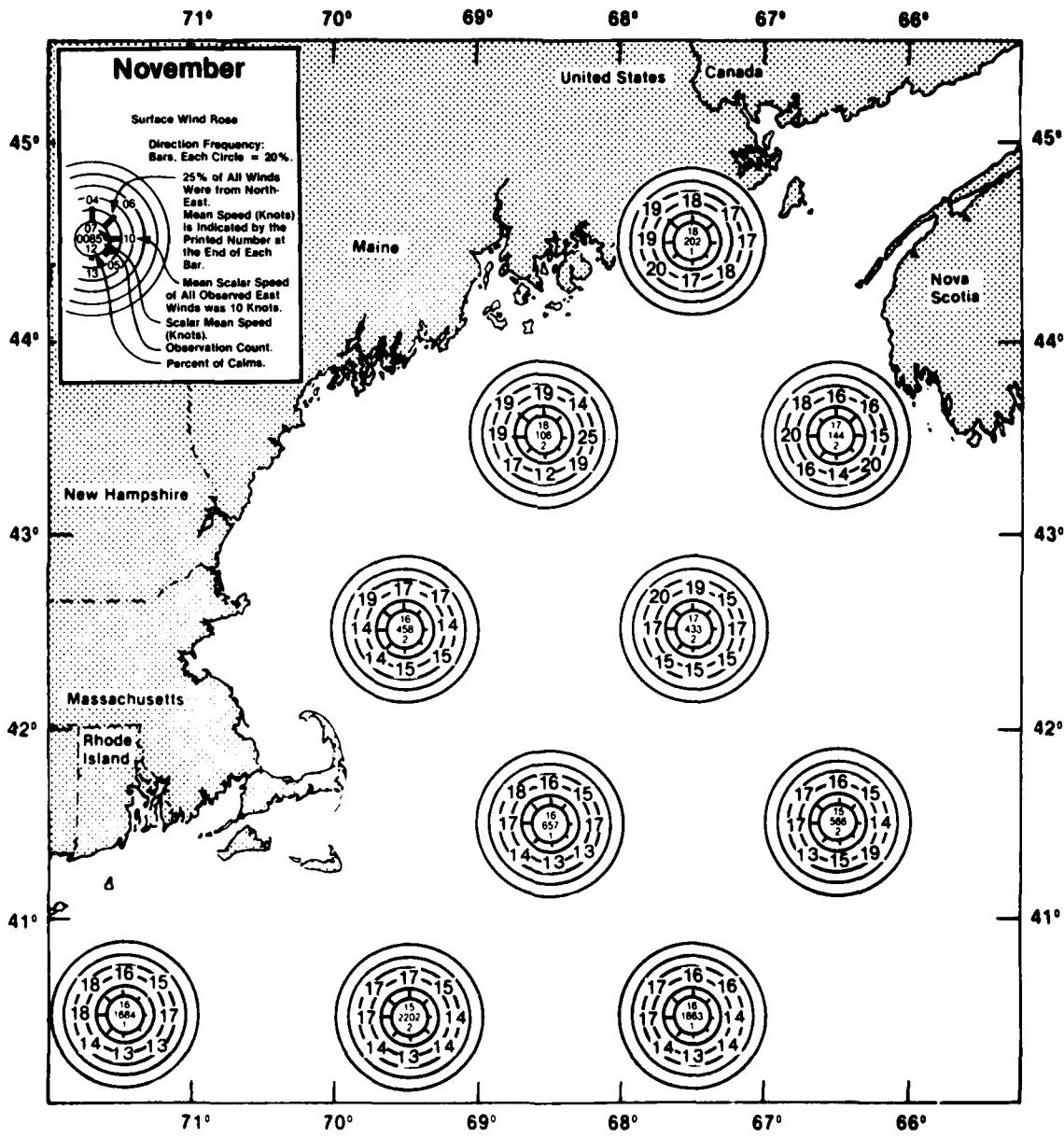


Figure 31.--November surface wind roses (after the National Weather Service, 1976).

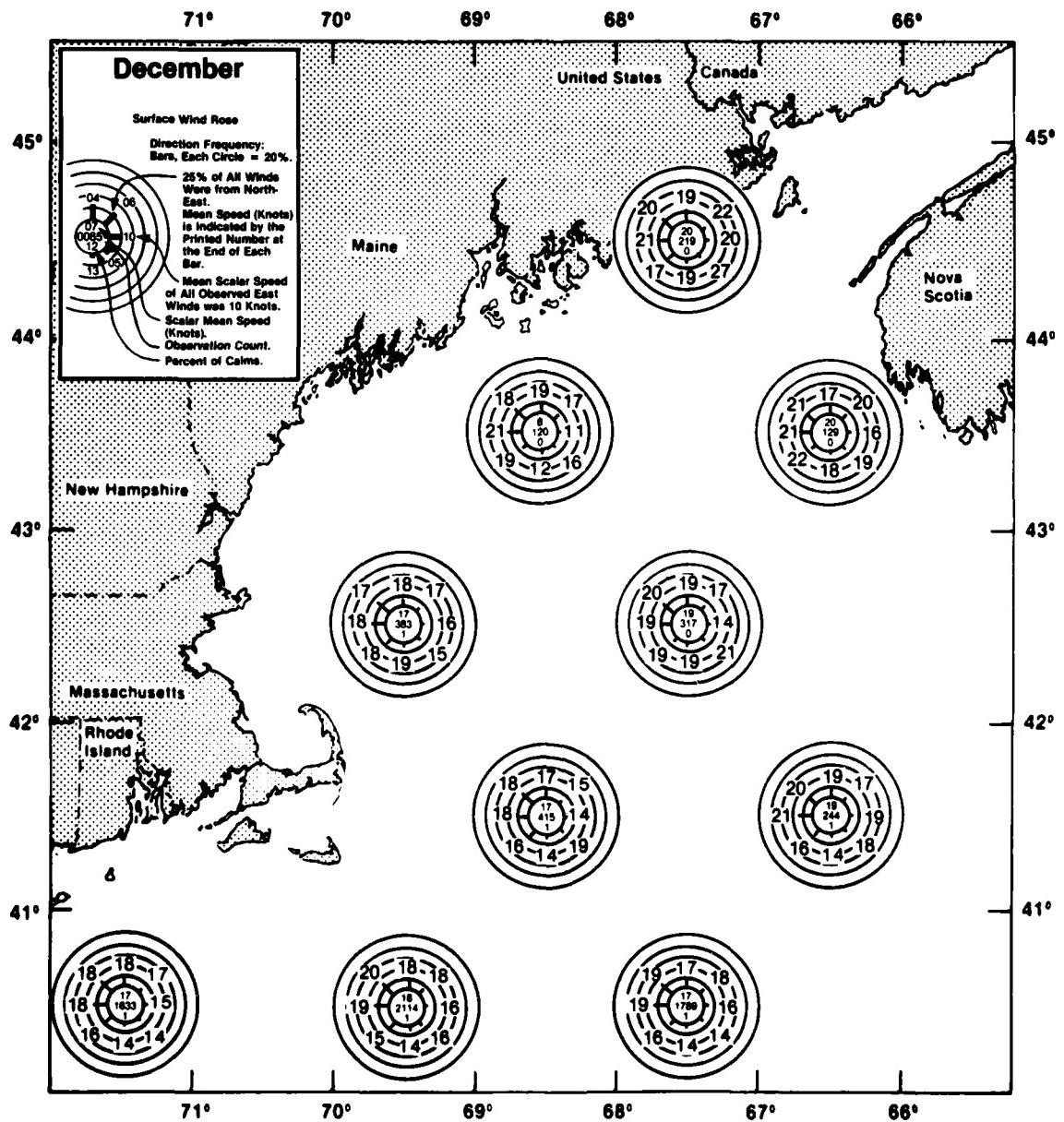


Figure 32.--December surface wind roses (after the National Weather Service, 1976).

unidirectional tendency than those of winter and fall. The tendency generally agrees with the calculations of variability given by Godshall et. al. (1980). Hence, oil spills in spring and summer can be expected to be advected with a higher probability in the mean wind direction than in winter and fall.

### 3.2 Fog

Another important environmental factor in connection with oil spill mitigation considerations is visibility. Visibility, or visual range, is commonly defined as the maximum distance at which a prominent object can be seen against the background. Visual range is important to one who must make plans concerning offshore marine operation during an oil spill. In the study region, restrictions to visibility that are commonly reported are precipitation, fog and spray.

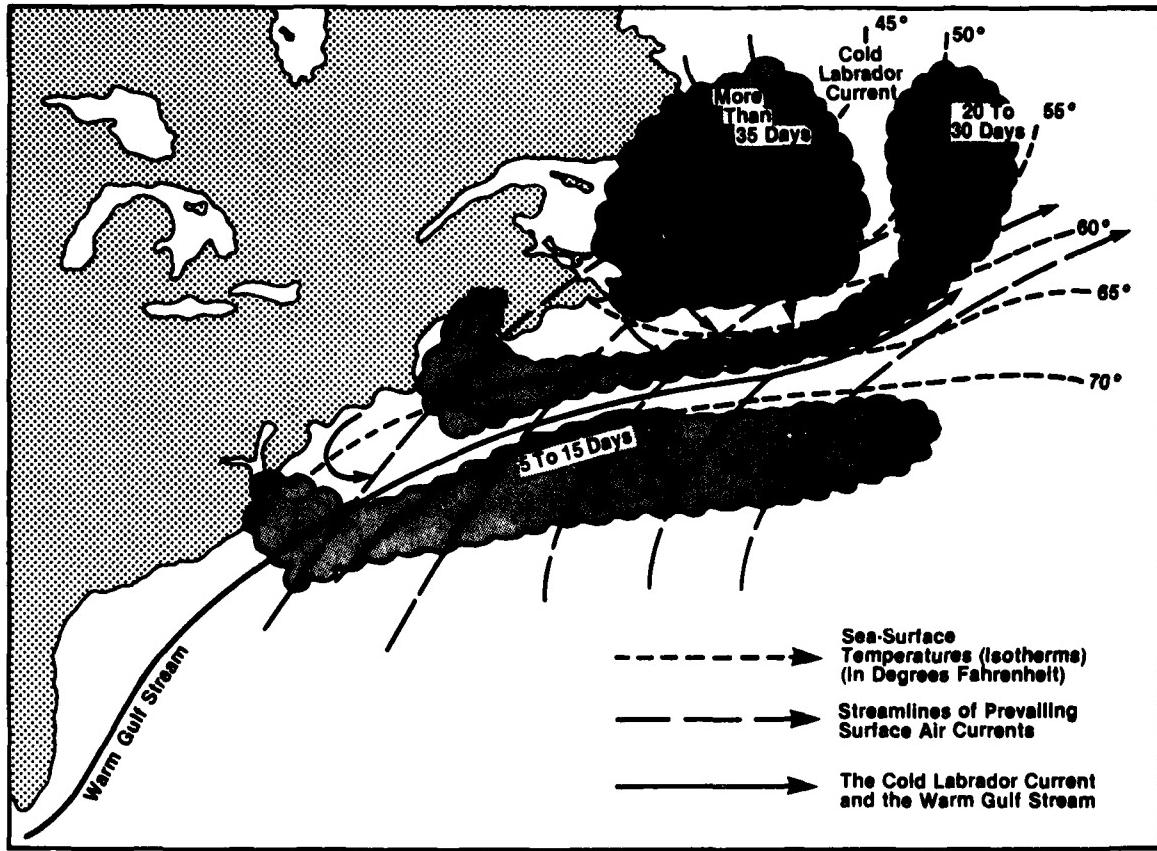
The formation of fog over the Gulf of Maine and Georges Bank is a commonly known phenomenon. This fog is attributed to condensation caused by warm air passing over cold water surfaces. The combination of cold water in the Gulf of Maine and the Scotian Shelf creates the potential for advection fog. During spring and summer, the prevailing wind over the region is from the southwest, which tends to produce air movement from warm to cooler water surface areas (Figure 33).

### 3.3 Wind Waves

Ocean waves have an important influence on the eventual fate and cleanup of spilled oil at sea. Wind waves provide surface turbulence which mixes a surface slick into the water column. Also, because of the exponential decay of wave particle velocity with depth, particles on wave crests move slightly forward compared with those at the trough, resulting in a slight wave-induced drift (about 1 percent of wind speed) in the downwind direction.

Because of the coastline, the Gulf of Maine is fetch-limited (waves cannot grow to the theoretical maximum for a given wind speed) to the west and north; thus, for a given duration, maximum waves would not be expected when the wind is from these directions. Monthly wave roses in this area are shown in Figure 34. Despite apparent fetch limitation to this area from the north and northwesterly direction, the occurrence of the larger waves ( $>3$  m) from these directions is evident.

During the winter (January) the wave propagation direction over the study region is predominantly 2.0 m for the entire region, while for the summer it is approximately 1.0 m. Georges Bank exhibits wave characteristics of a zone of transition from deep water areas to the south and east within the Gulf of Maine. In the summer (July), the wind is predominantly from the south or southwest. A seasonal pattern of large ( $> 3$  m) waves propagating from the northwest and west during winter and of significantly smaller waves ( $< 2$  m) propagating from the south and southwest in the summer months is observed (Figure 35).



**Figure 33.--Formation of fog over the North Atlantic Ocean during the summer months (after Kotch, 1970).**

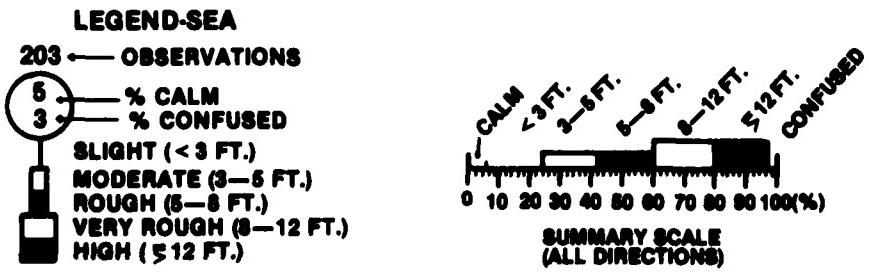
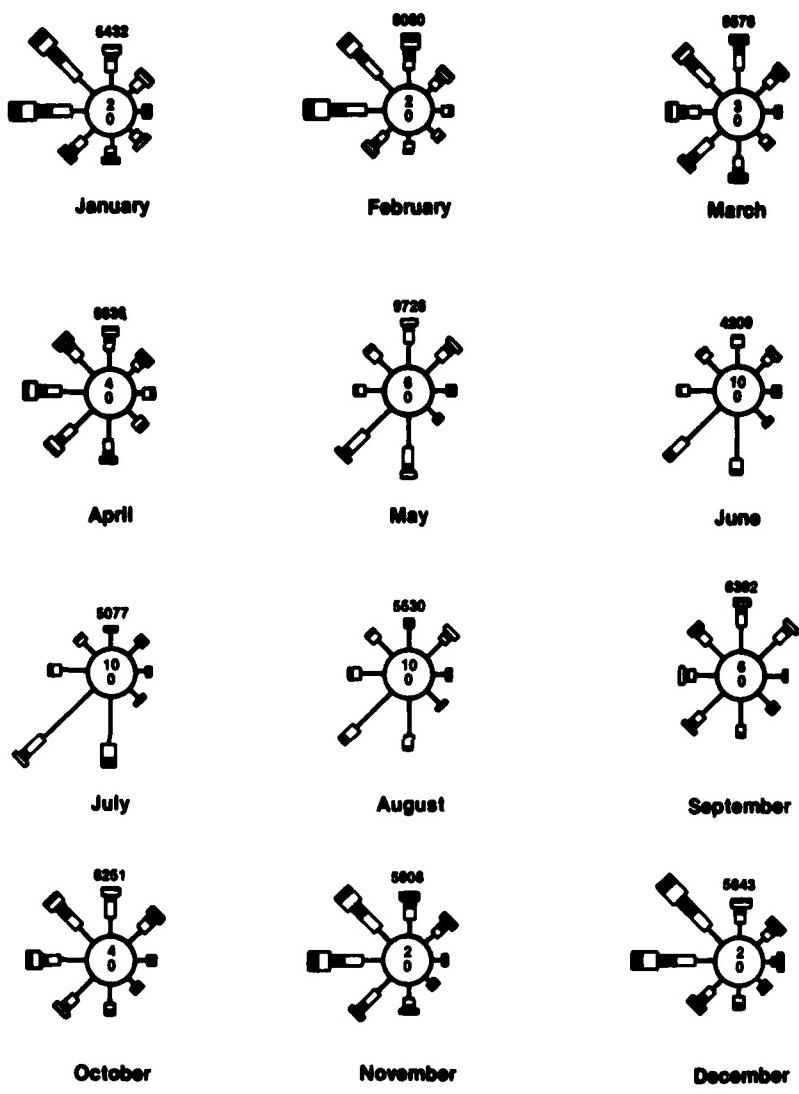


Figure 34.--Monthly wave roses (after Godshall et. al., 1980).

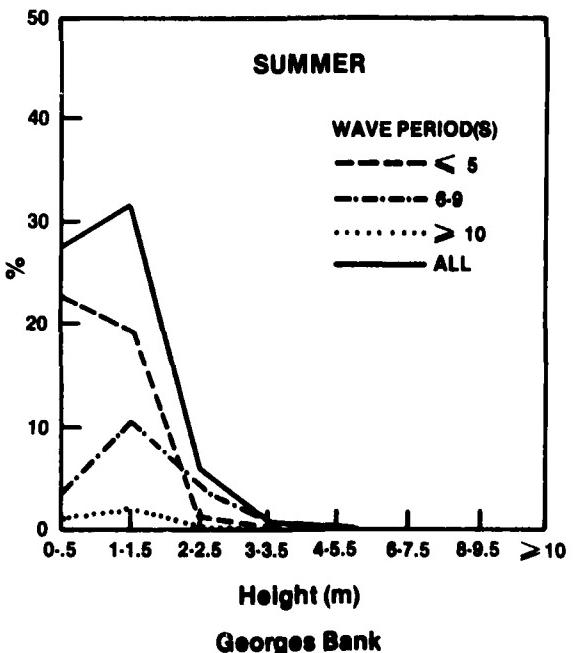
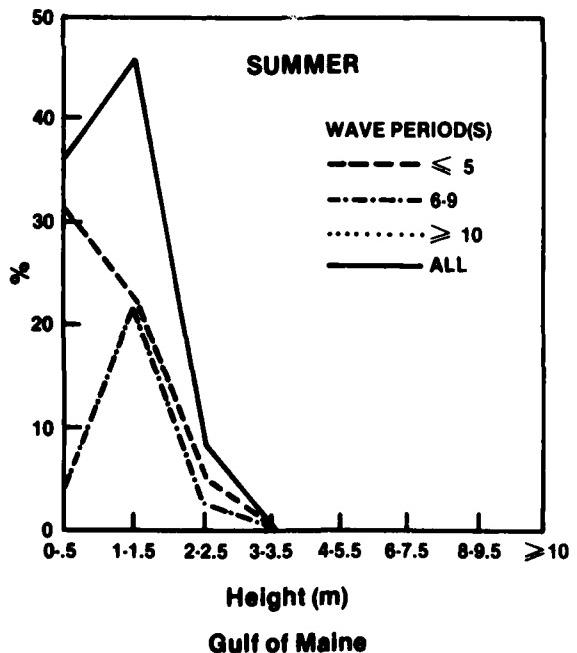
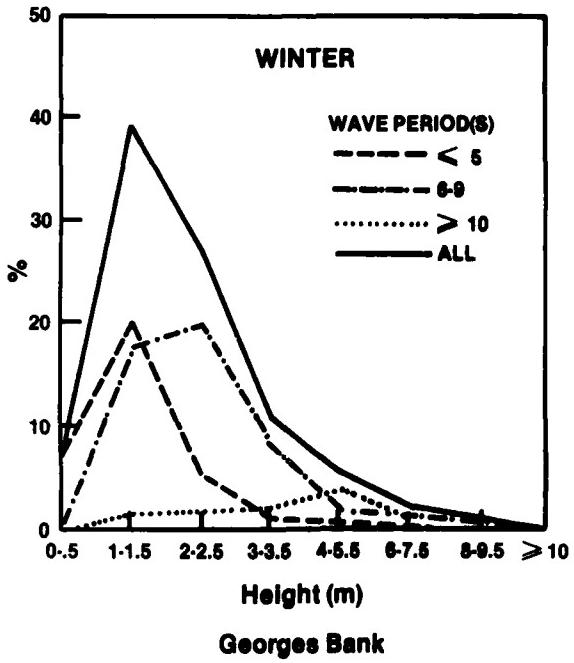
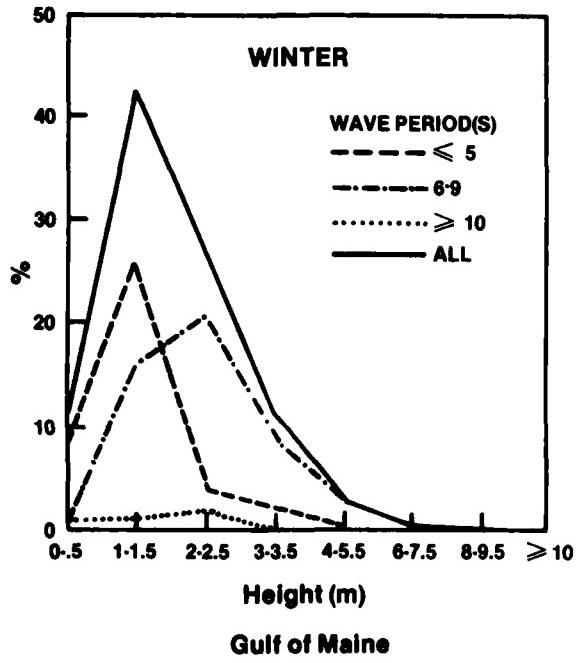


Figure 35.--Typical winter/summer wave height - period histograms  
(after Godshall et. al., 1980).

### 3.4 Water Temperatures

#### 3.4.1 Temperature Distribution

The mixing rate of oil in the water is related to water temperature in that higher temperatures increase mixing. Also, because of the relationship between water temperature and circulation features, temperature gradients usually coincide with circulation boundaries.

Because of increased wind mixing in the winter, a vertically constant temperature is observed throughout the water column with the coldest surface water near shore, increasing offshore.

In coastal waters (< 100 m in depth), a rapid vertical change of temperature (thermocline) appears in May and continues to intensify to a maximum temperature difference of about 7°C in early September. Thus, during the summer the water column is at a point of minimum mixing ability (maximum stability). Figures 36 to 47 show the mean monthly temperature distribution for the Gulf of Maine/Georges Bank area at the sea surface and at a depth of 100 m. Figures 48 to 51 indicate average temperatures cross-sectional slices through the study area.

#### 3.4.2 Sea-Surface Temperature (remote sensing techniques)

The "average" picture of water temperatures presented in the previous section is clearly an oversimplification that tends to smooth out the convoluted fronts and sharp gradients which may exist. The complexity of the sea surface temperature structure in this region has been confirmed by high resolution satellite imagery.

One operational product based on these satellite images is the analysis produced by the USCG Oceanographic Unit, the U.S. Navy and NOAA (Figure 52). Each analysis, based on several days of observation, shows the position of the major thermal fronts, the locations of cold and warm eddies, and identifies the different water masses. These charts show that conditions can range from the relatively simple to the complicated. For information concerning this analyses one should contact:

NOAA/NESS S132  
Director, Environmental Products Branch  
World Weather Bldg., Room 510  
Washington, D.C. 20233

Satellites are extremely valuable tools to map large scale circulation features such as permanent currents, water mass boundaries and large eddies, but they do have limitations.

1. At best, they record only the skin temperature of the ocean as opposed to the bulk temperature measured by ordinary immersed thermometers. Except during periods of unusual calm, the normal

stirring by waves eliminates this as a serious problem. However, even bulk surface temperatures are not reliable indicators of deeper temperature patterns.

2. More serious is the effect of atmospheric water vapor on satellite measurements. These errors can be corrected to some extent by using an assumed water vapor profile from a model atmosphere. A better solution will have two infrared bands that respond quite differently to water vapor. The differences in measured radiance can be used to determine the atmospheric correction. It is expected that absolute temperatures should be accurate to about 1 C.
3. Cloud cover is a serious limitation to satellite mapping, since sea-surface temperatures can be observed only when the satellite pass happens to coincide with a cloud-free period. Oceanic phenomena change more slowly than those in the atmosphere so that the continually improving coverage in time will eliminate much of this problem, except for periods of extended cloud cover.

A second technique for mapping sea-surface temperatures is the use of airborne radiation thermometer (ART). This technique, employed by the Coast Guard Oceanographic Unit, is useful in locating the region of sharp gradients, such as those that occur near major current boundaries and large scale eddies. Except for special studies, ART data should be supplemented by satellite imagery which provides broader coverage and is more nearly instantaneous over a large area.

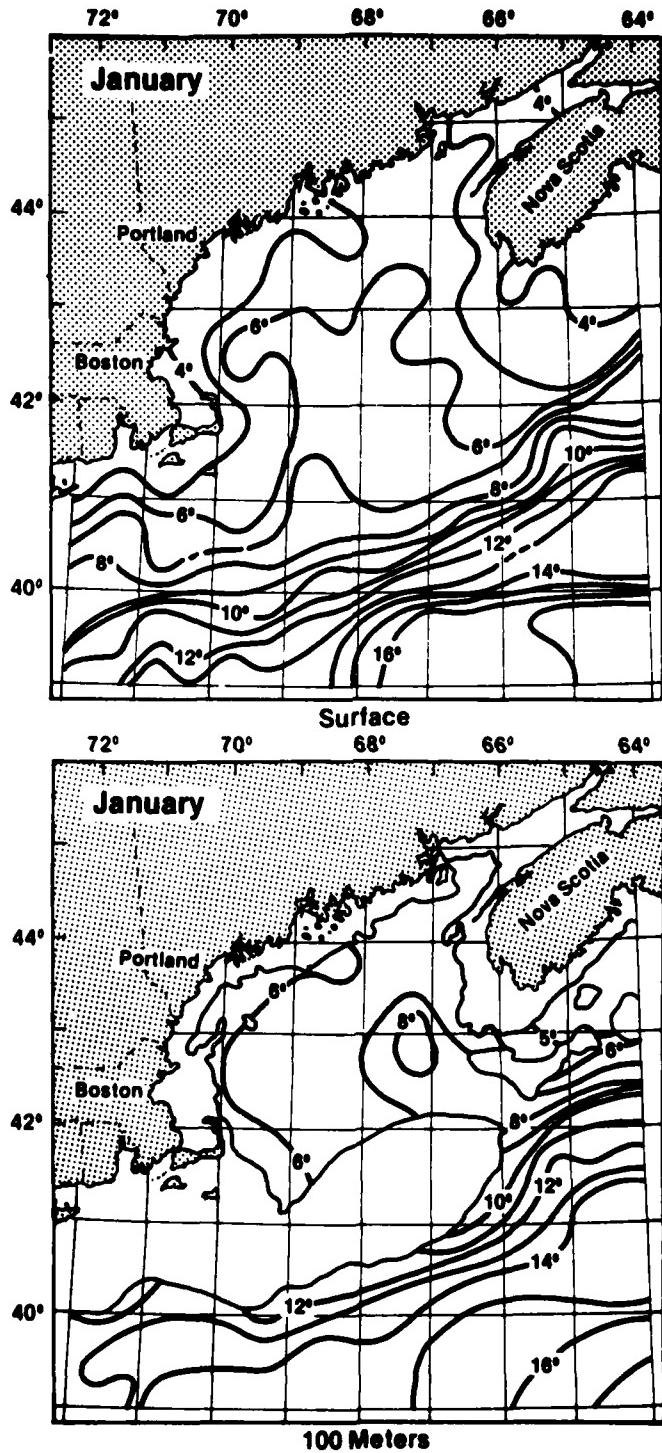
For climatological purposes, the best regular reports on sea-surface temperature are provided by "Gulfstream", a monthly publication of the National Weather Service. These reports are based on available information from ships, aircraft and satellites. Each issue includes a schematic drawing of the locations of the oceanic fronts and eddies, a selection of bathythermograms (BTs) and charts giving the mean surface temperature for the month, anomaly from the 100-year mean for the month, and the change from the previous month, all on a one-degree grid from 25°N to 45°N and 55°W to 85°W.

### 3.5 Salinity Distribution

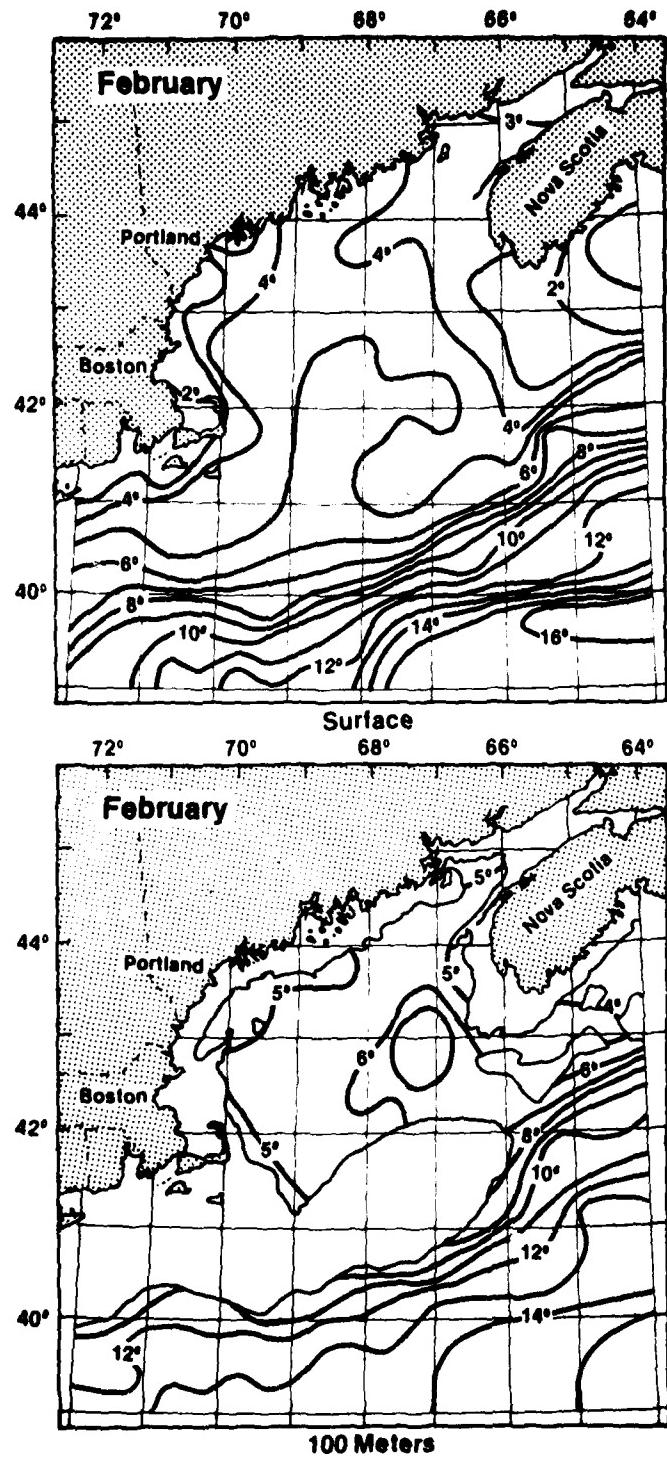
The observed salinity distribution is a result of the balance between river runoff, evaporation minus precipitation, advection, and mixing. Salinity in coastal waters is at a maximum at the end of winter (owing to subfreezing conditions on the continent) and at a minimum in early summer (because of spring runoff). Figures 53 to 56 show both surface and 125 meter salinity fields for the study region.

### 3.6 Density Distribution

In the Gulf of Maine/Georges Bank region, the water reaches its maximum density during the winter months because of the annual minimum in temperature and maximum in salinity. In the spring, warming of the surface water with a



**Figure 36.--January temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).**



**Figure 37.--**February temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).

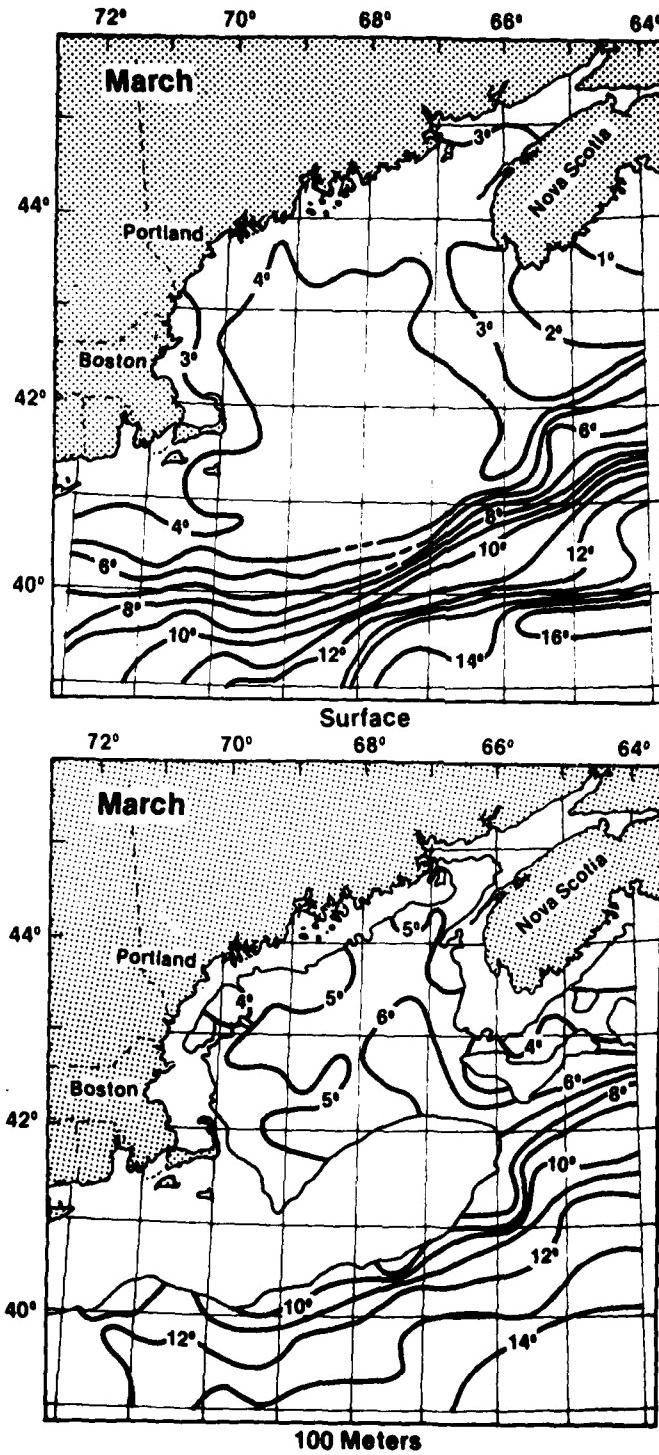
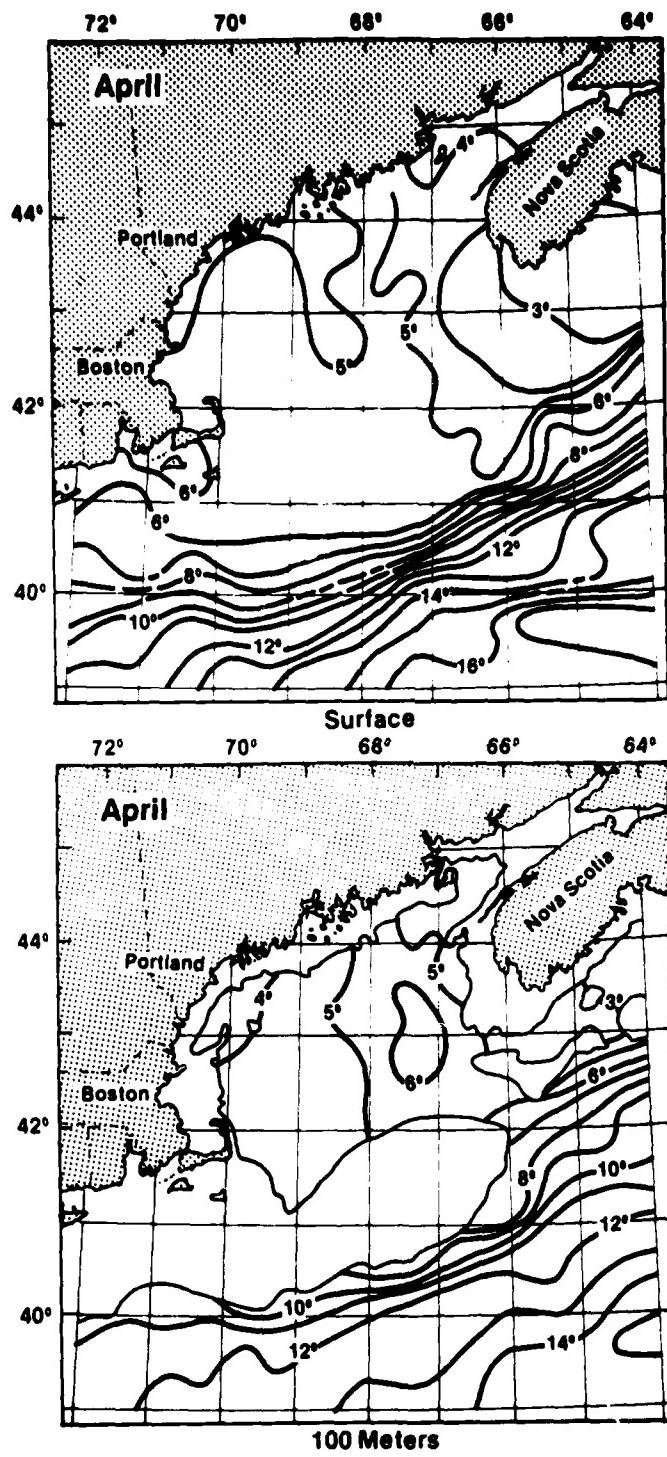
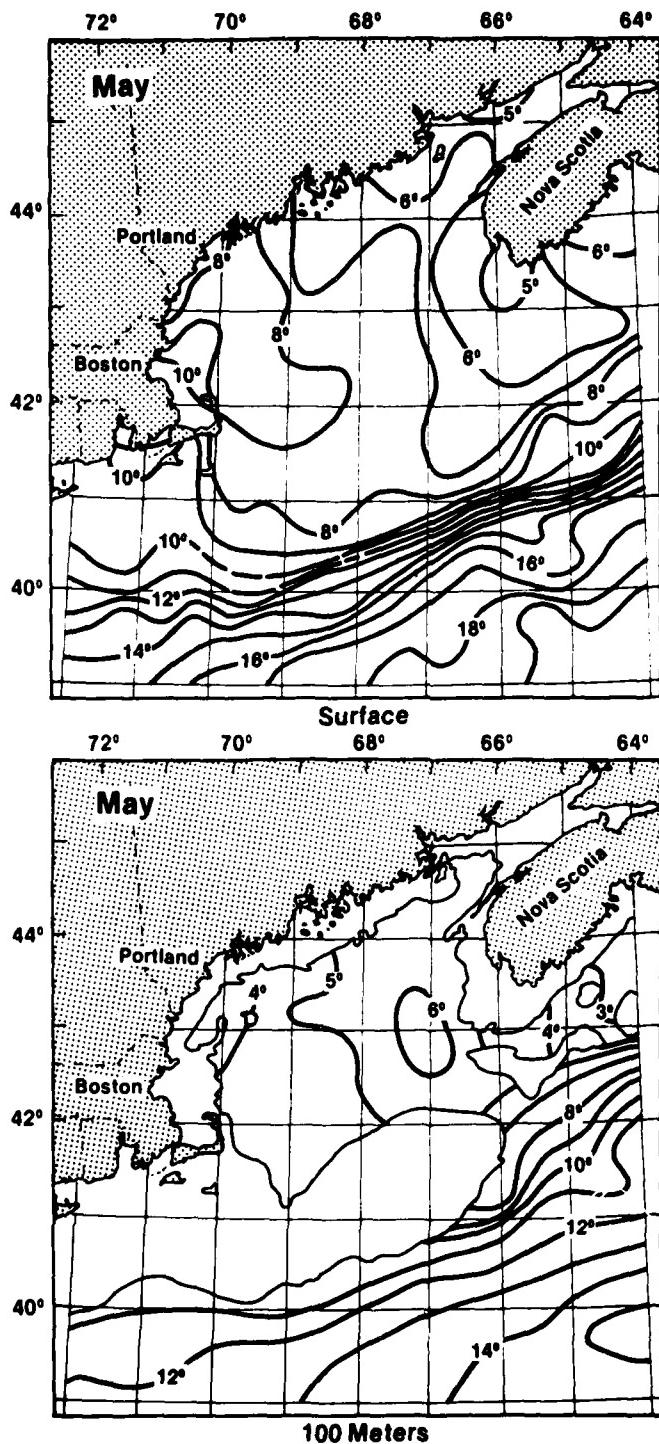


Figure 38.--March temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).



**Figure 39.--April temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).**



**Figure 40.--**May temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).

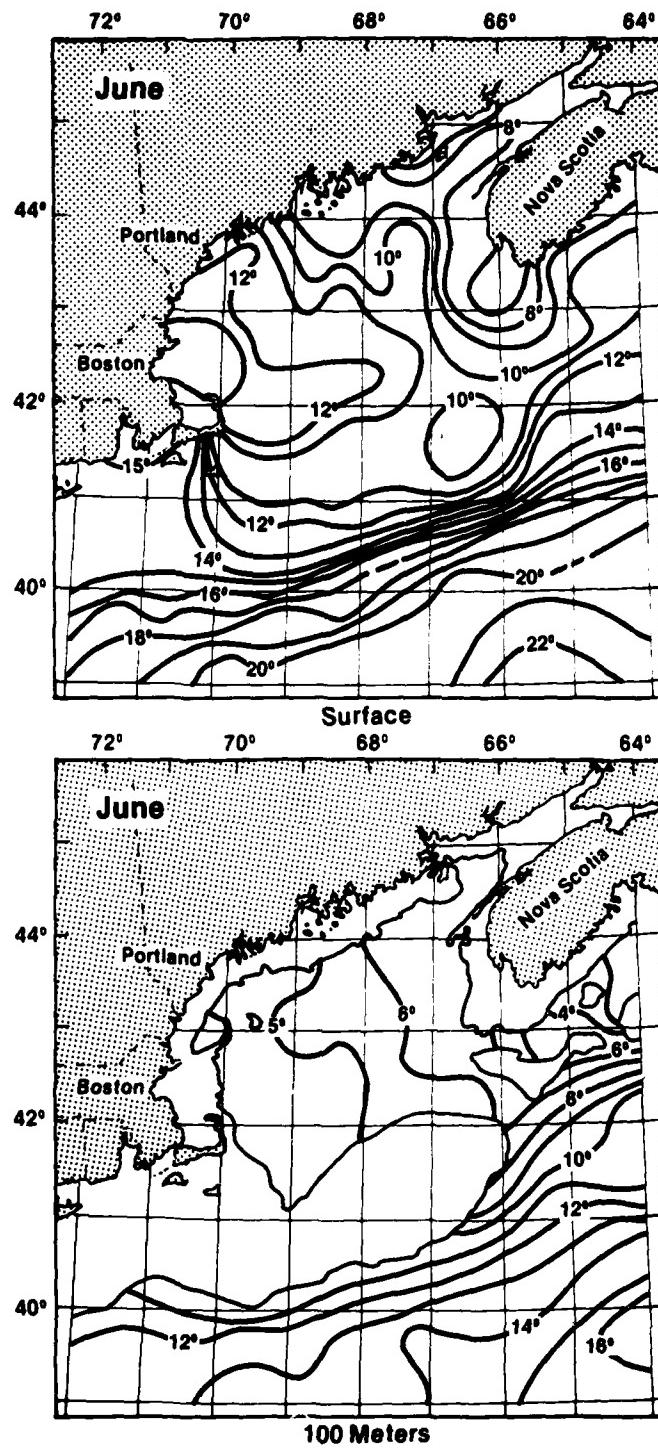
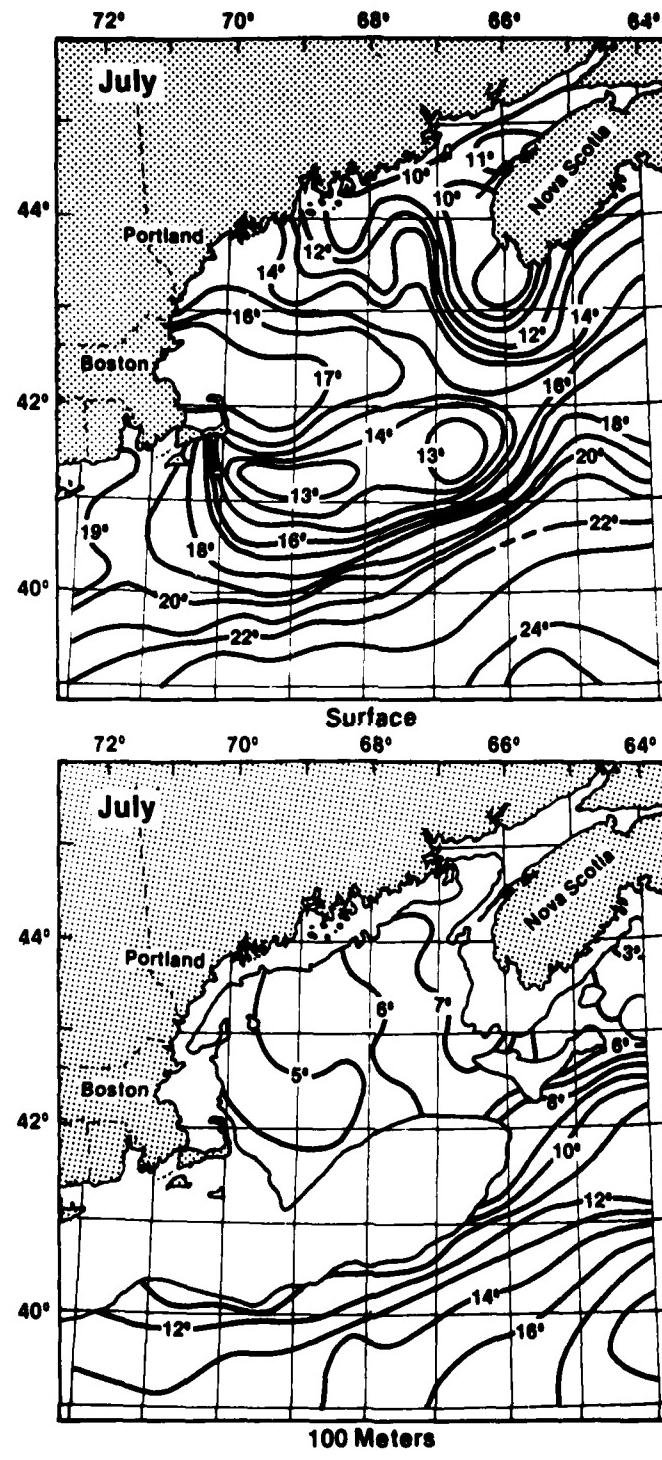


Figure 41.--June temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).



**Figure 42.--July temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).**

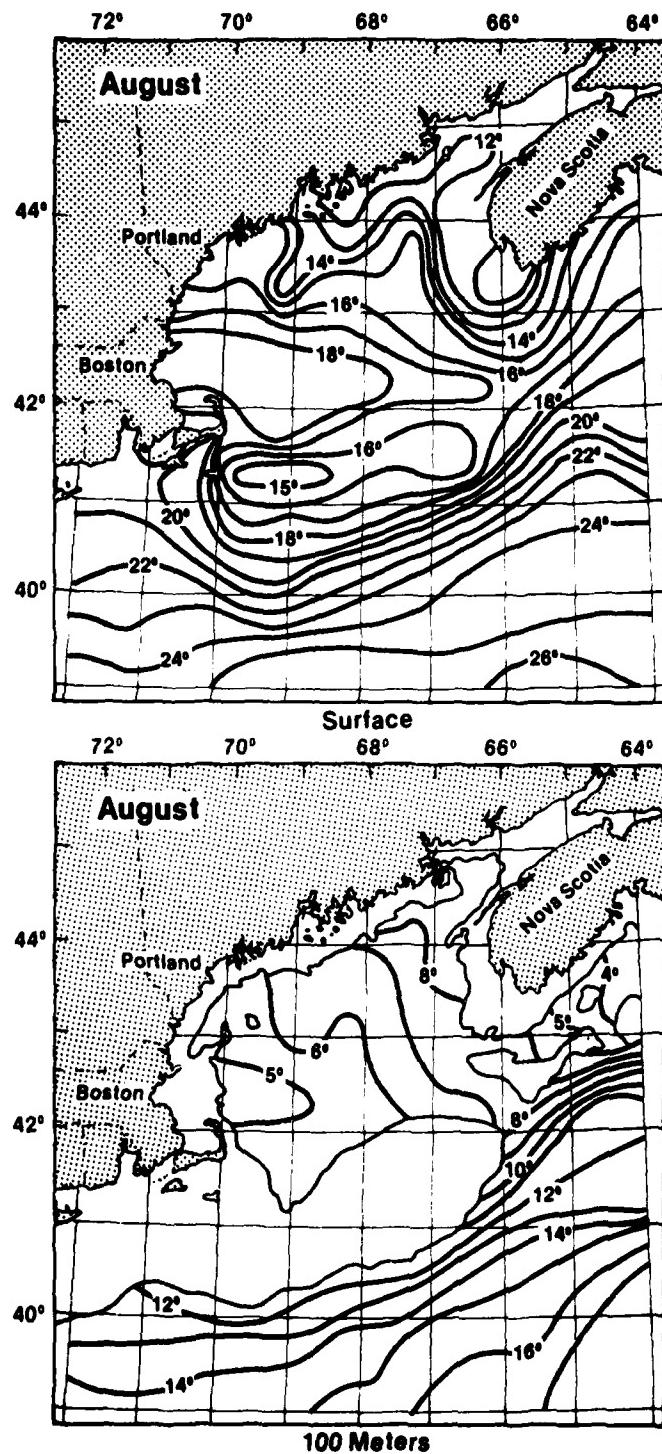
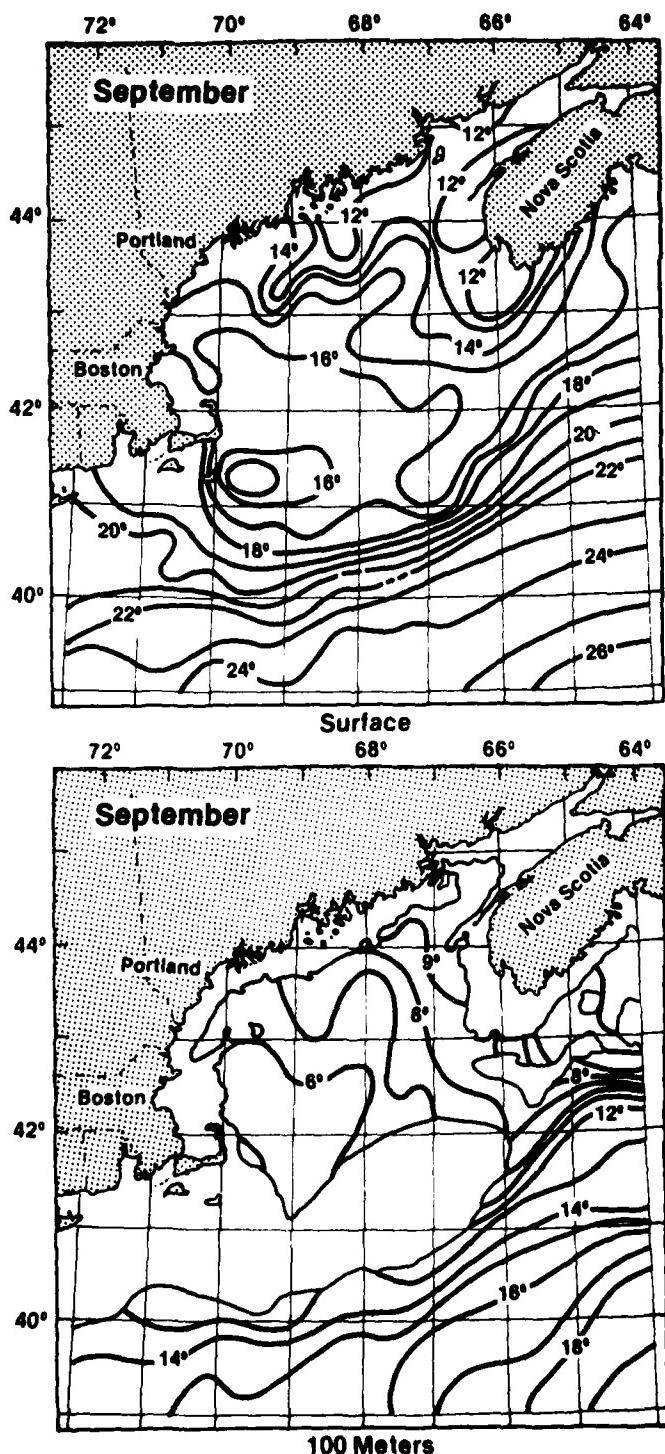


Figure 43.--August temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).



**Figure 44.--September temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).**

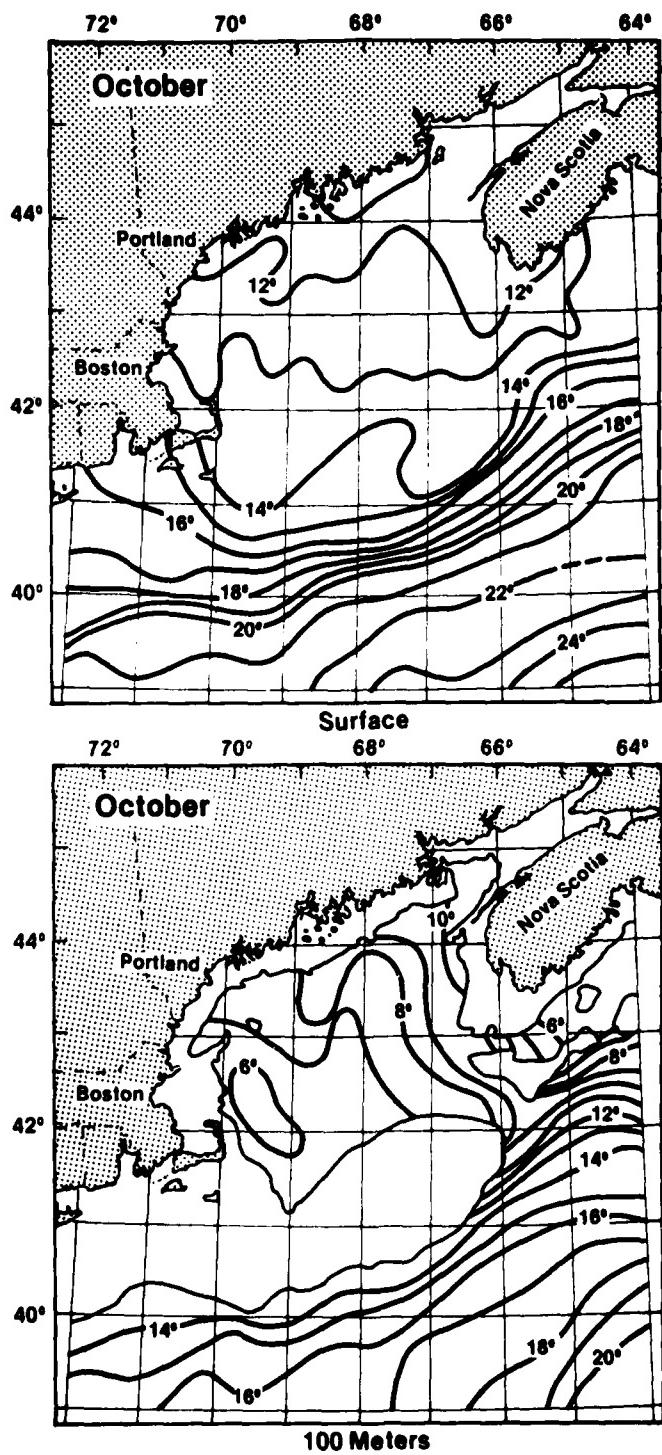


Figure 45.--October temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).

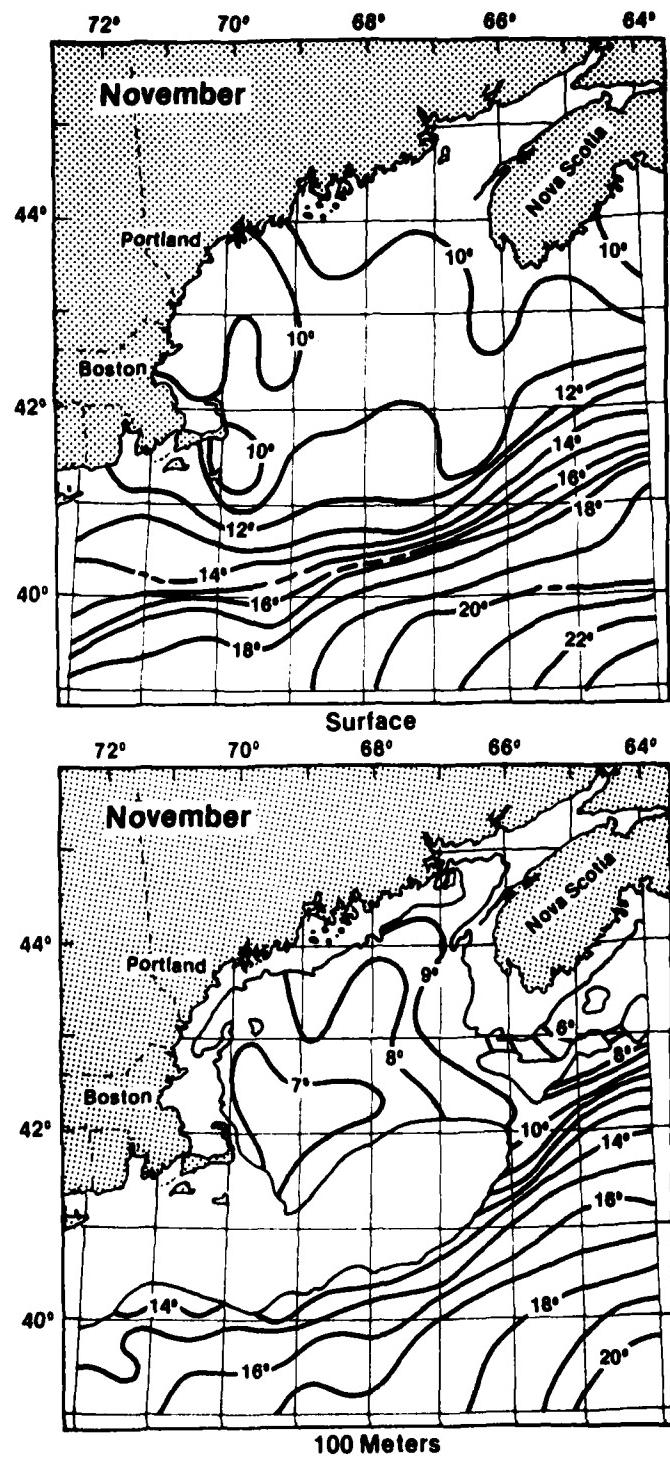
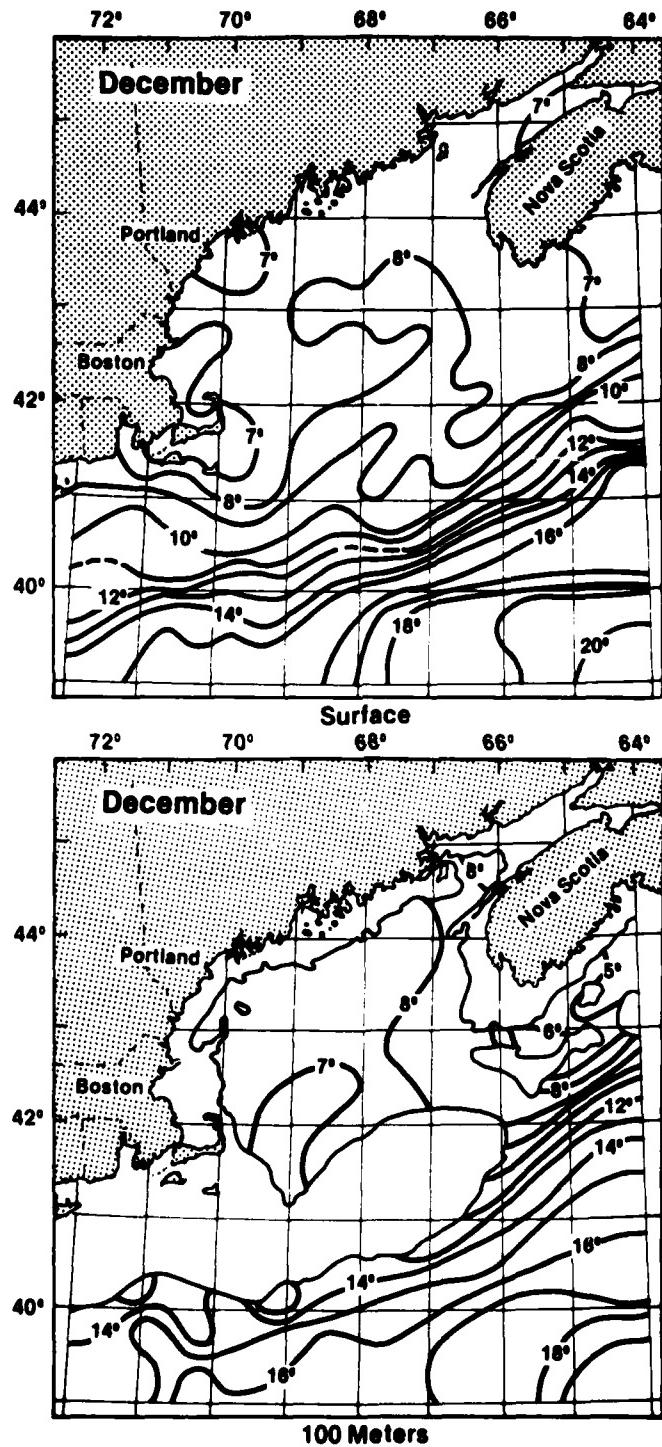
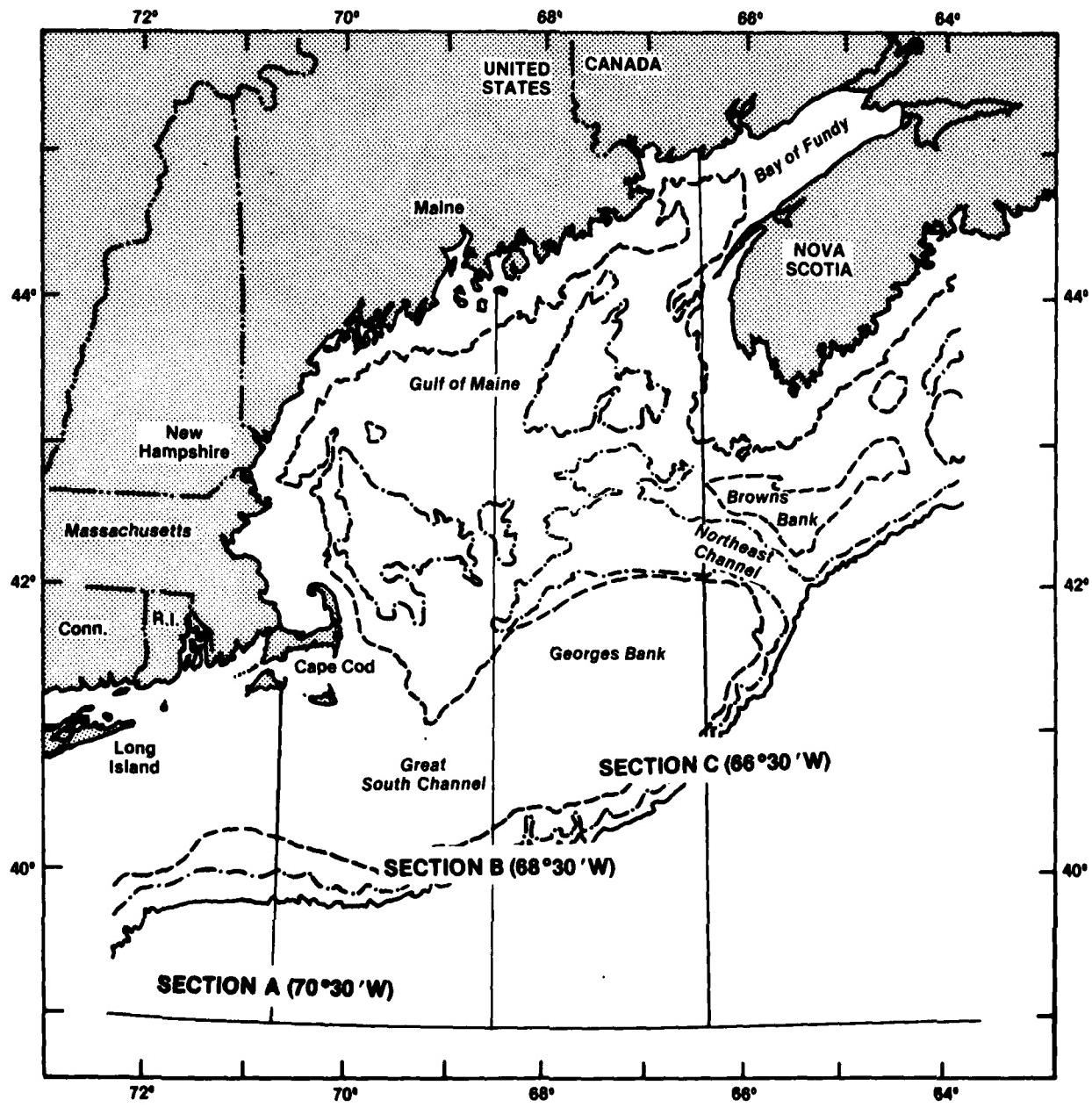


Figure 46.--November temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).



**Figure 47.--December temperature isotherms at surface and 100 meters (after Colton and Stoddard, 1972).**



**Figure 48.--Cross-sections used for temperature profiles (after Colton and Stoddard, 1972).**

SECTION A (70°30'W)

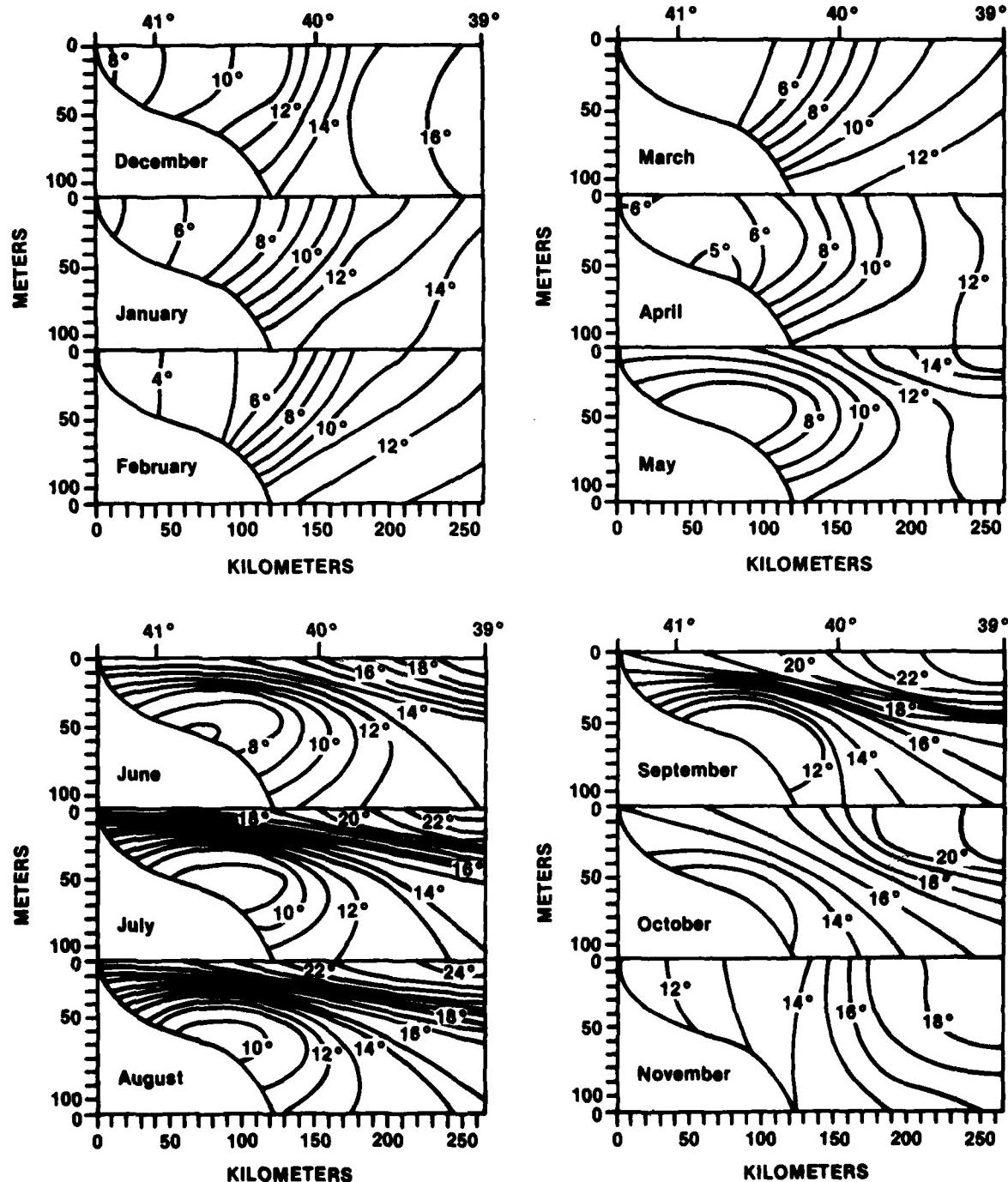
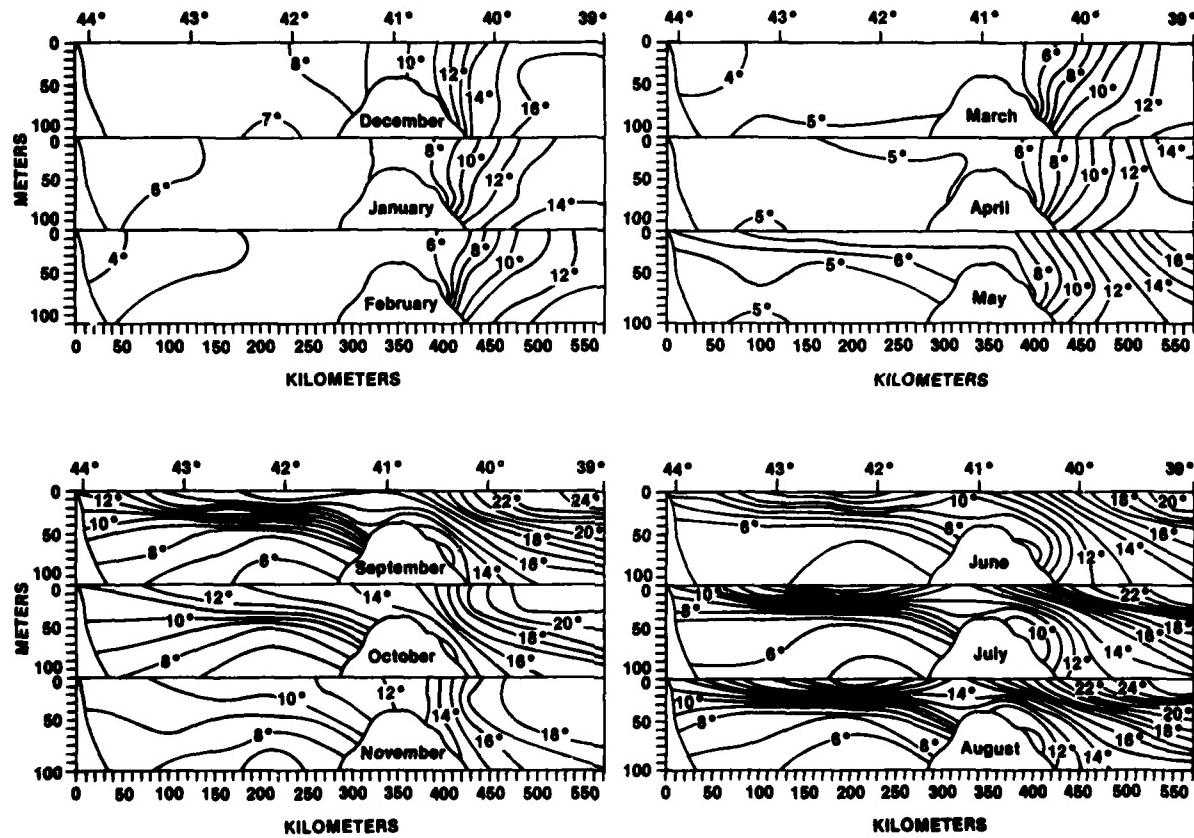


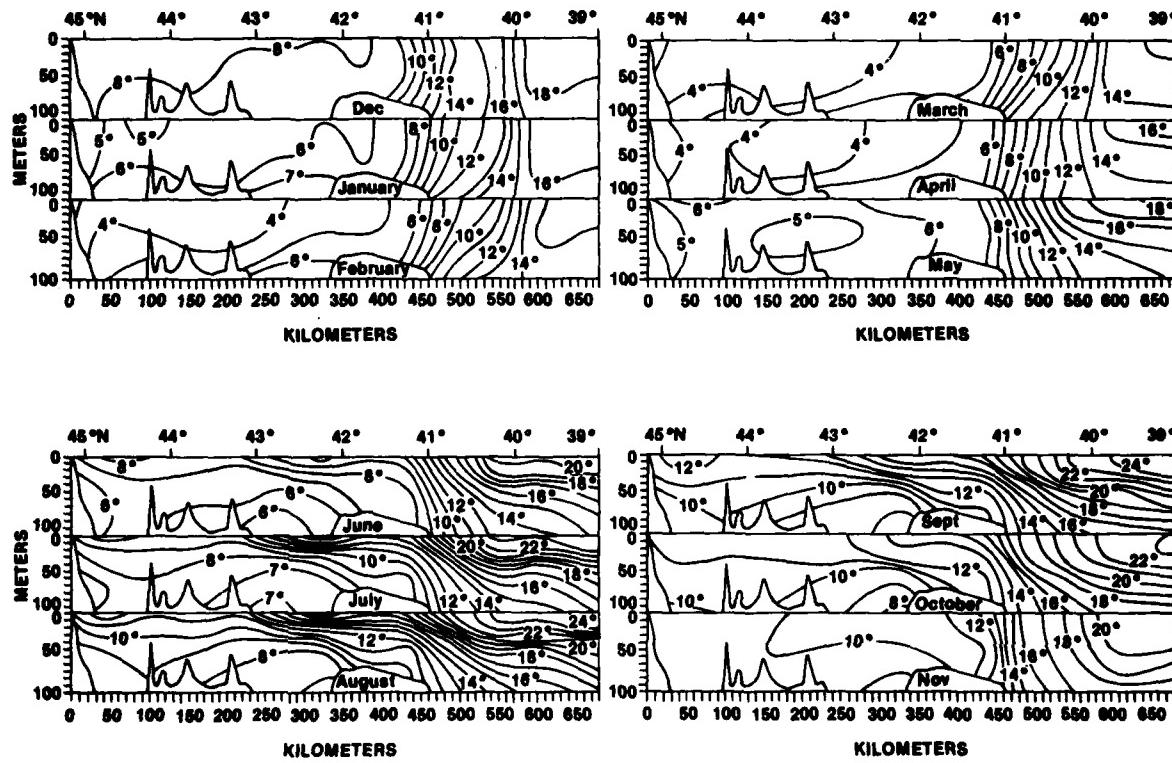
Figure 49.--Monthly mean temperature profiles (after Colton and Stoddard, 1972).

**SECTION B (68°30' W)**



**Figure 50.--Monthly mean temperature profiles (after Colton and Stoddard, 1972).**

**SECTION C (66°30' W)**



**Figure 51.--Monthly mean temperature profiles (after Colton and Stoddard, 1972).**

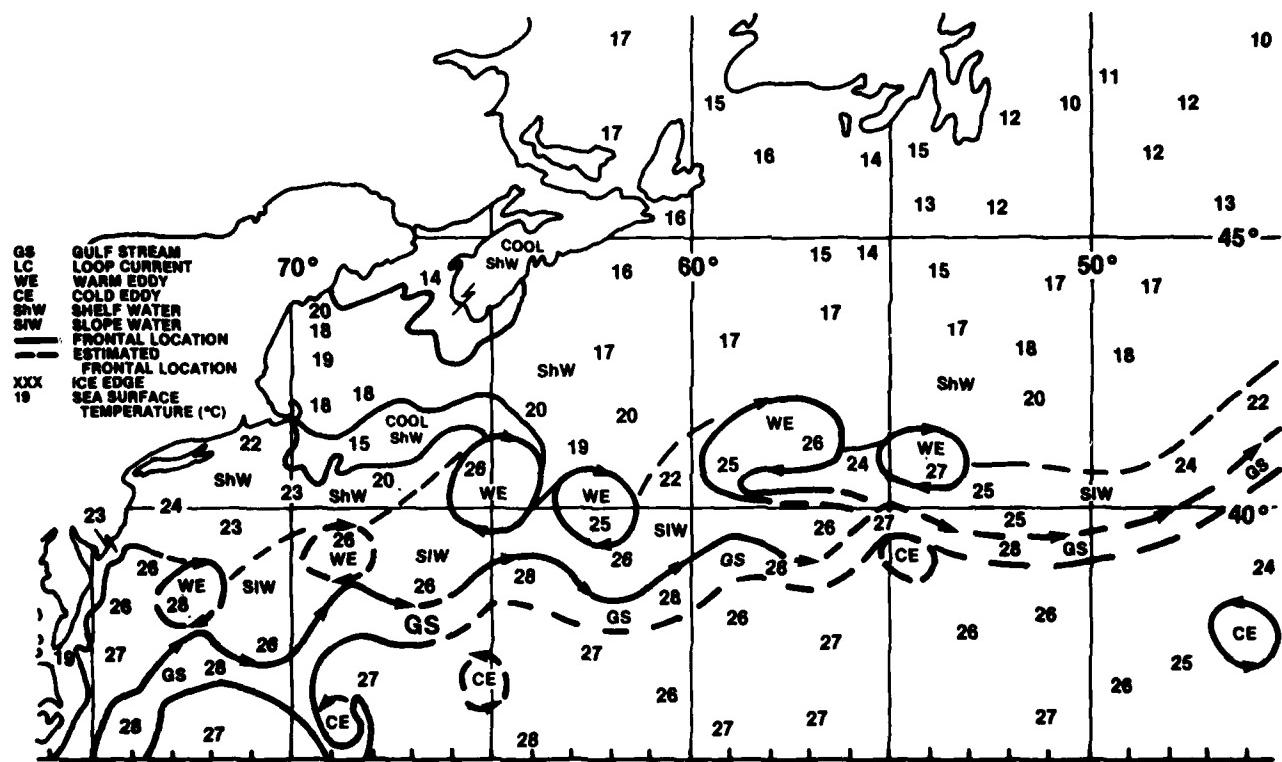
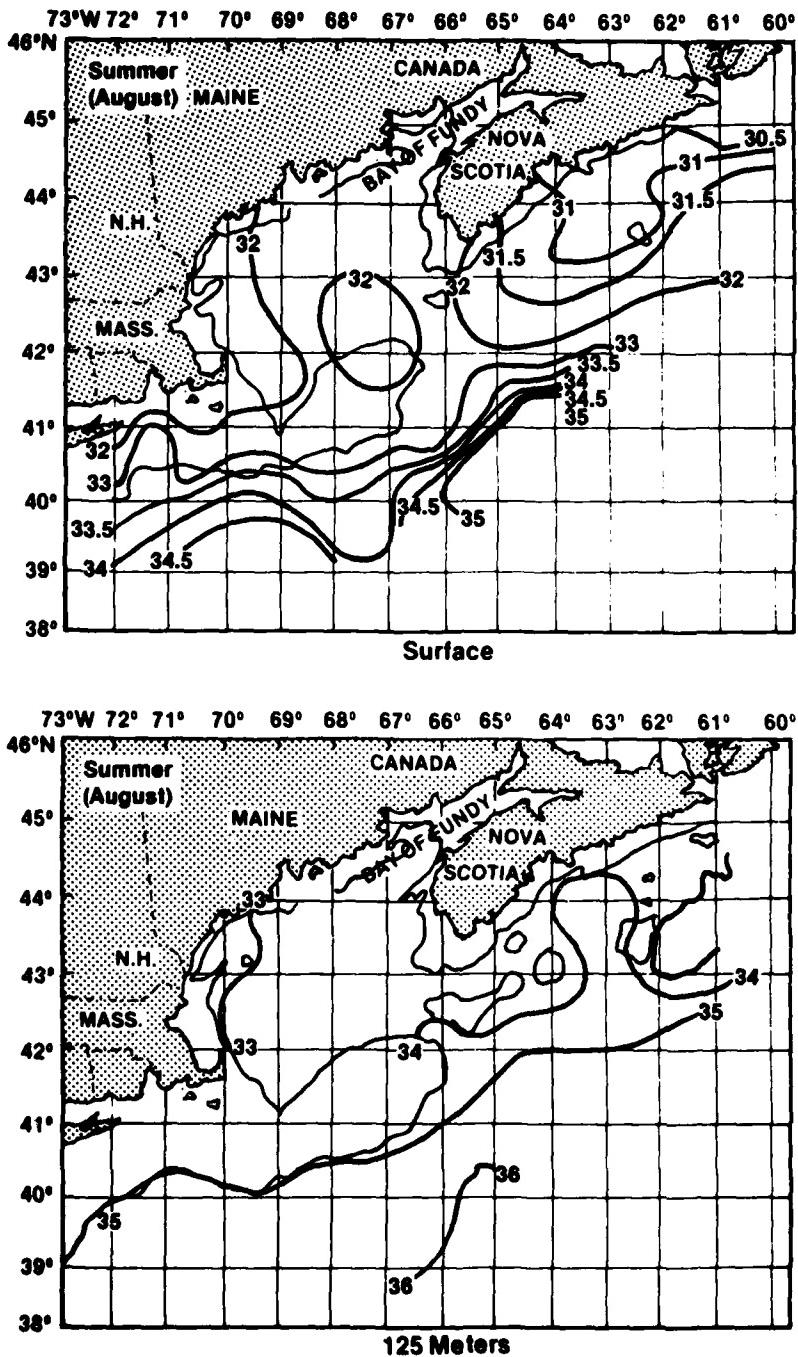


Figure 52.--Oceanographic Analysis for August 13, 1980 (after U.S. Coast Guard, 1980).



**Figure 53.--**Mean seasonal isohalines at surface and at 125 meters (after Godshall et. al., 1980).

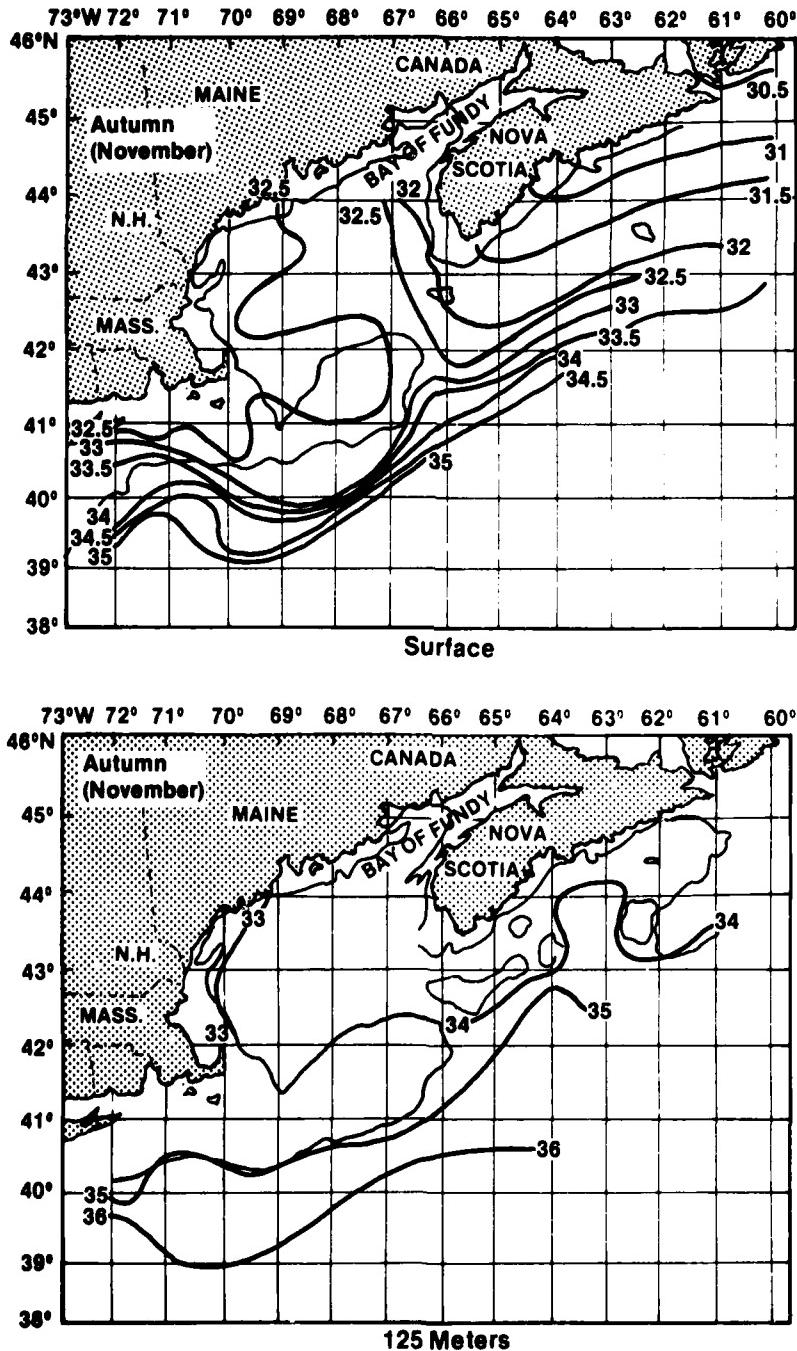


Figure 54.--Mean seasonal isohalines at surface and at 125 meters (after Godshall et. al., 1980).

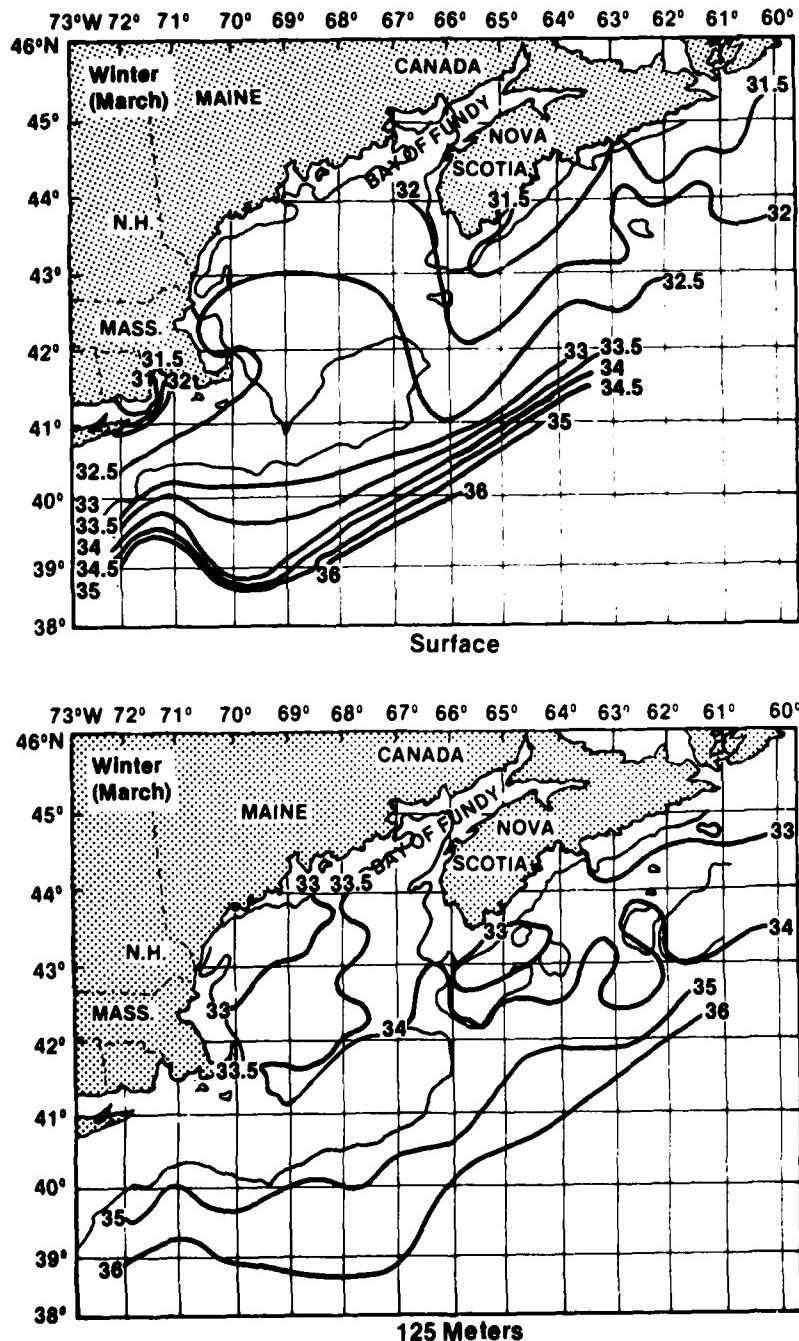


Figure 55.--Mean seasonal isohalines at surface and at 125 meters (after Godshall et. al., 1980).

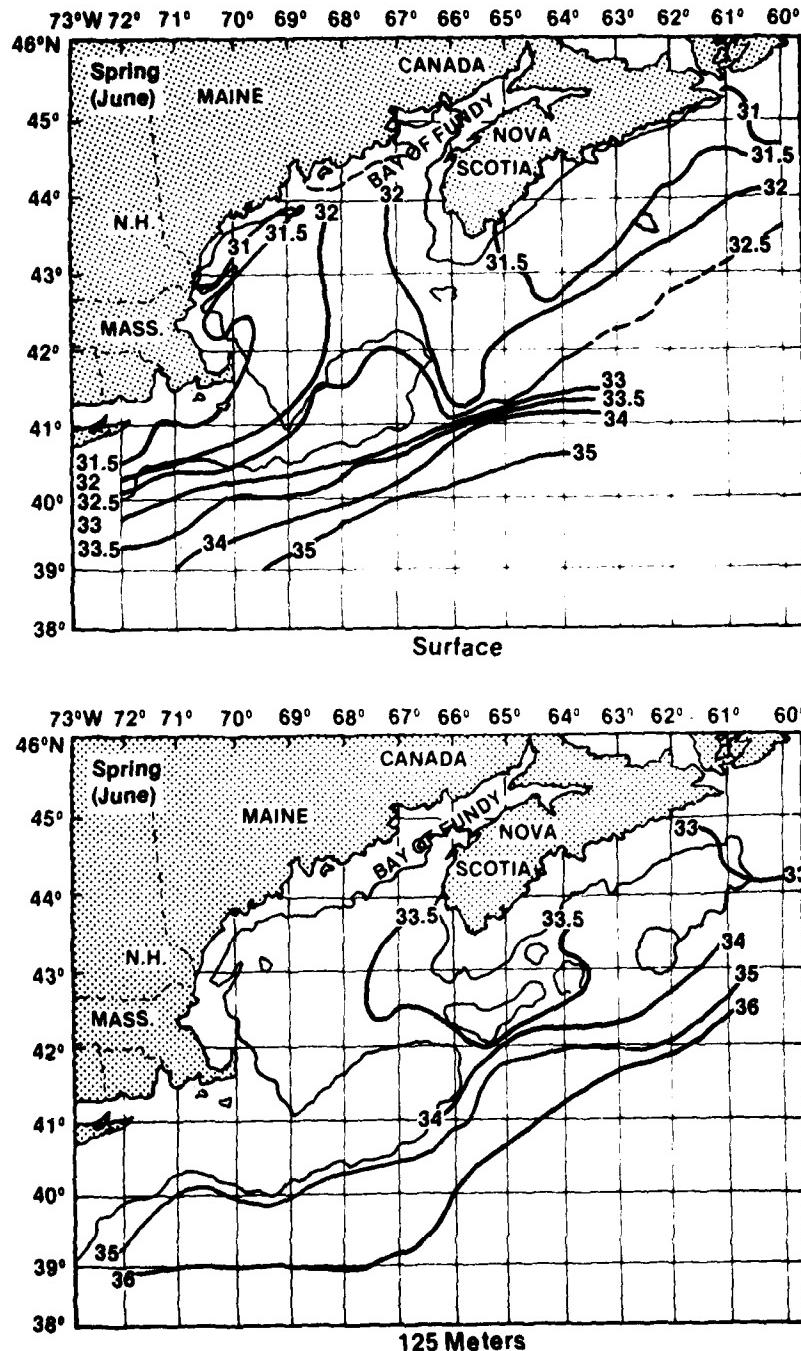


Figure 56.--Mean seasonal isohalines at the surface and at 125 meters  
(after Godshall et. al., 1980).

large increase in runoff produce a marked vertical and horizontal stratification of the water column. The horizontal stratification drives a southward-directed coastal flow that increases in magnitude (i.e. 10-15 cm/sec) into late summer. This mean density-driven current may be important in the long-term advection of an oil spill at sea during calm periods. The vertical stratification leads to a development of a sharp density change (pycnocline). This develops (as does the thermocline) in May and continues to increase in intensity to a maximum in September. This condition causes oil spilled in the mixed layer (in the upper 10-15 meters) to be trapped above the strong pycnocline at 15-30 meters. Figures 57 and 58 show typical vertical density profiles for the Gulf of Maine/Georges Bank regions.

### 3.7 Vertical Mixing

Vertical mixing of oil in the ocean can occur by convective processes, by mechanical stirring such as surface wind-wave mixing, by tidal current mixing, or by diffusion. Vertical mixing is a function of the density stratification and of the vertical turbulence.

Implications regarding the extent of vertical mixing are drawn from the analysis of water "stability",  $E$ , defined by Hesselberg and Sverdrup (1914) to be the vertical density gradient. Large positive values of  $E$  imply strong vertical stratification, which inhibits vertical mixing; small positive values of  $E$  imply deep vertical mixing, as caused, for example, by strong winter winds. Here  $E$  will be approximated by  $\Delta\sigma_t / \Delta Z$ , the vertical gradient of sigma-t [ $\sigma_t = (\text{density}-1) 1000$ ].

Typical vertical profiles of stability for the study area are given in Figures 59 and 60 for winter and summer.

Winter. In the winter, stability is low in the upper 40 m although variability is high. The water column, shown in Figure 59, has a maximum stability at about 70 meters. Strong wind mixing and surface cooling account for this occurrence. Stability below 100 meters (m) decreases smoothly to near zero in the bottom layers. During winter, density increases very gradually with depth, and mixing occurs throughout the water column on the shelf and down to the depth of penetration of seasonal influence on the slope ( $> 200$  m). These conditions lead to enhanced mixing of a surface oil spill throughout the first 40-70 m of the water column.

Summer. In the summer, stability is high for the near-surface water (within 20-30 m). Surface heating and inflow of river water are associated with a further increase near 40 meters. A sharp decrease in stability is shown below 40 m, slowly decreasing below 100 m until it nears zero at the bottom of the column. During this season, a surface oil spill will most probably be trapped in the upper mixed layer because of the development of the strong pycnocline and low wind velocity.

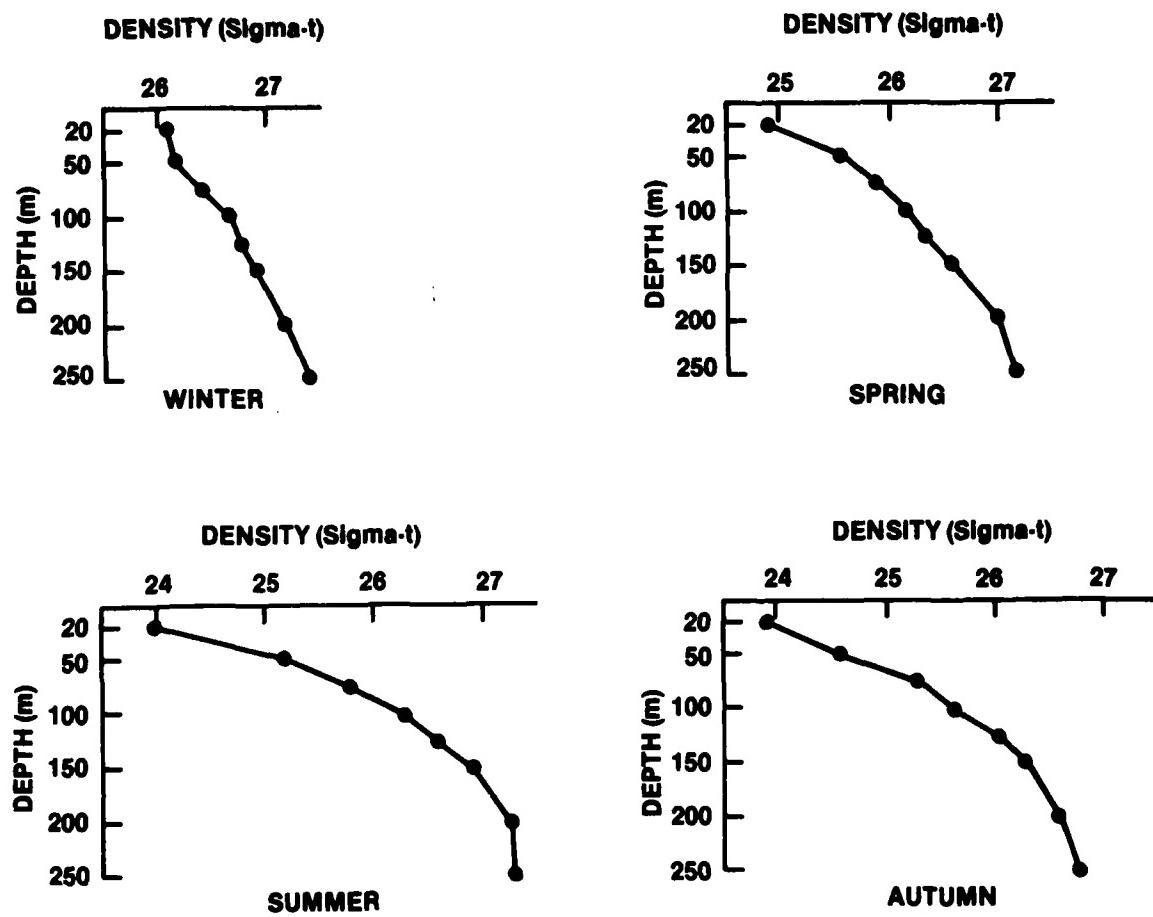


Figure 57.--Mean density profiles, Gulf of Maine (Lat.  $42.5^{\circ}\text{N}$  Long.  $67.5^{\circ}\text{W}$ )  
(after Godshall et. al., 1980).

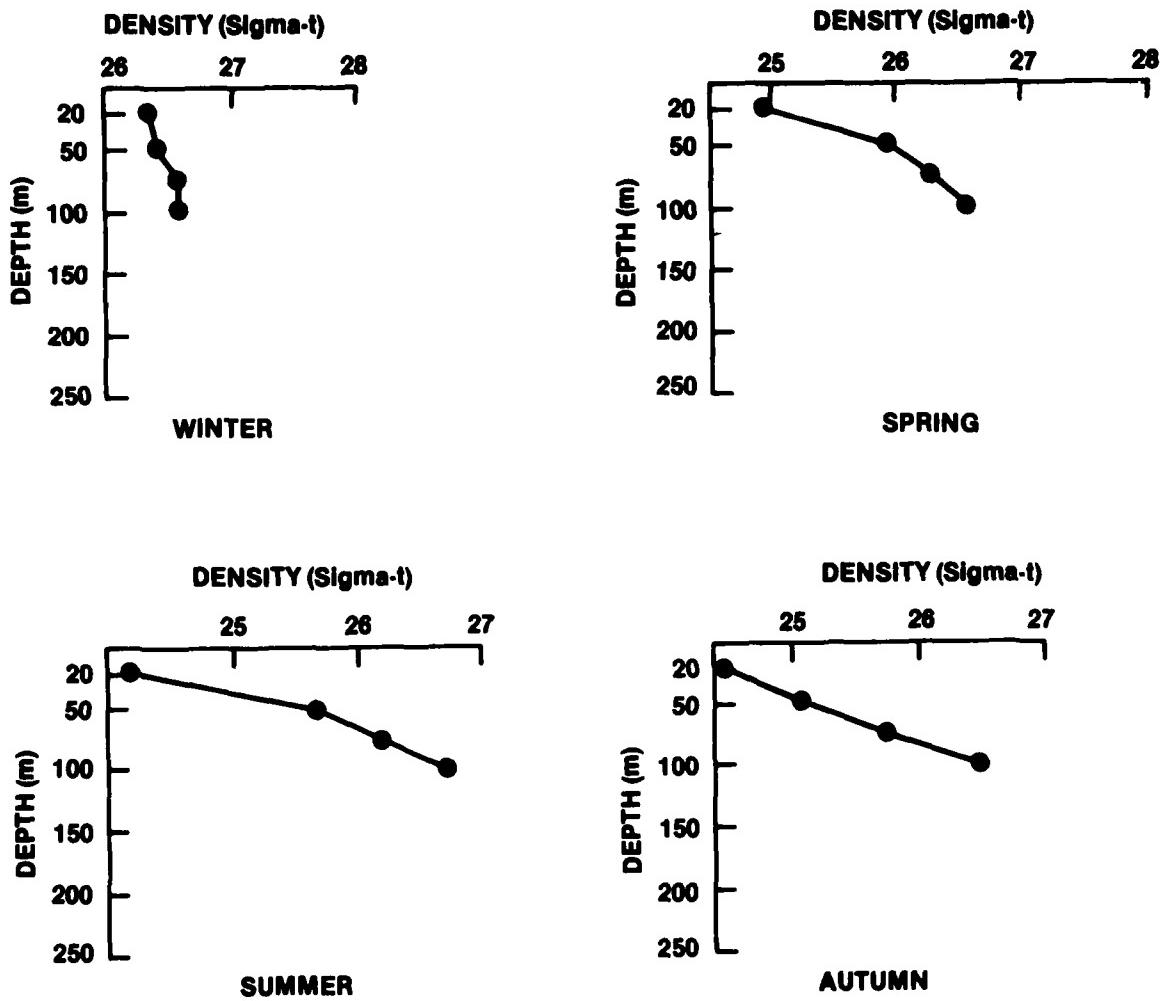


Figure 58.--Mean density profiles, Nantucket Shoals (Lat.  $40.5^{\circ}\text{N}$  Long.  $70.5^{\circ}\text{W}$ )  
(after Godshall et. al., 1980).

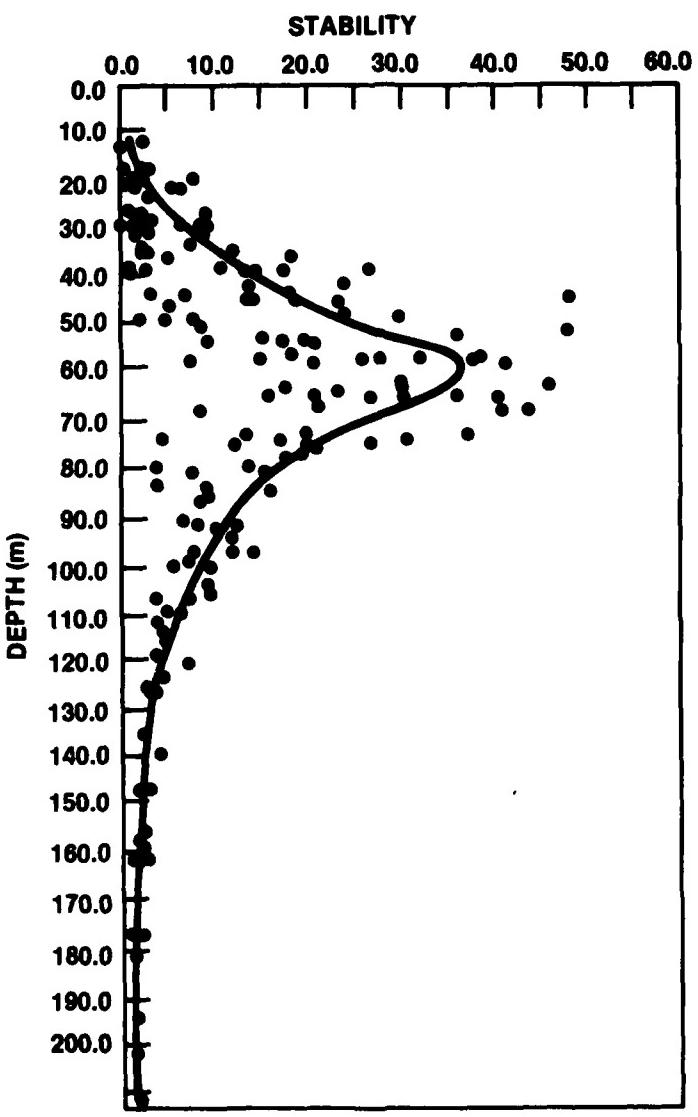


Figure 59.--Mean winter stability index profile, Gulf of Maine (after Godshall et. al., 1980).

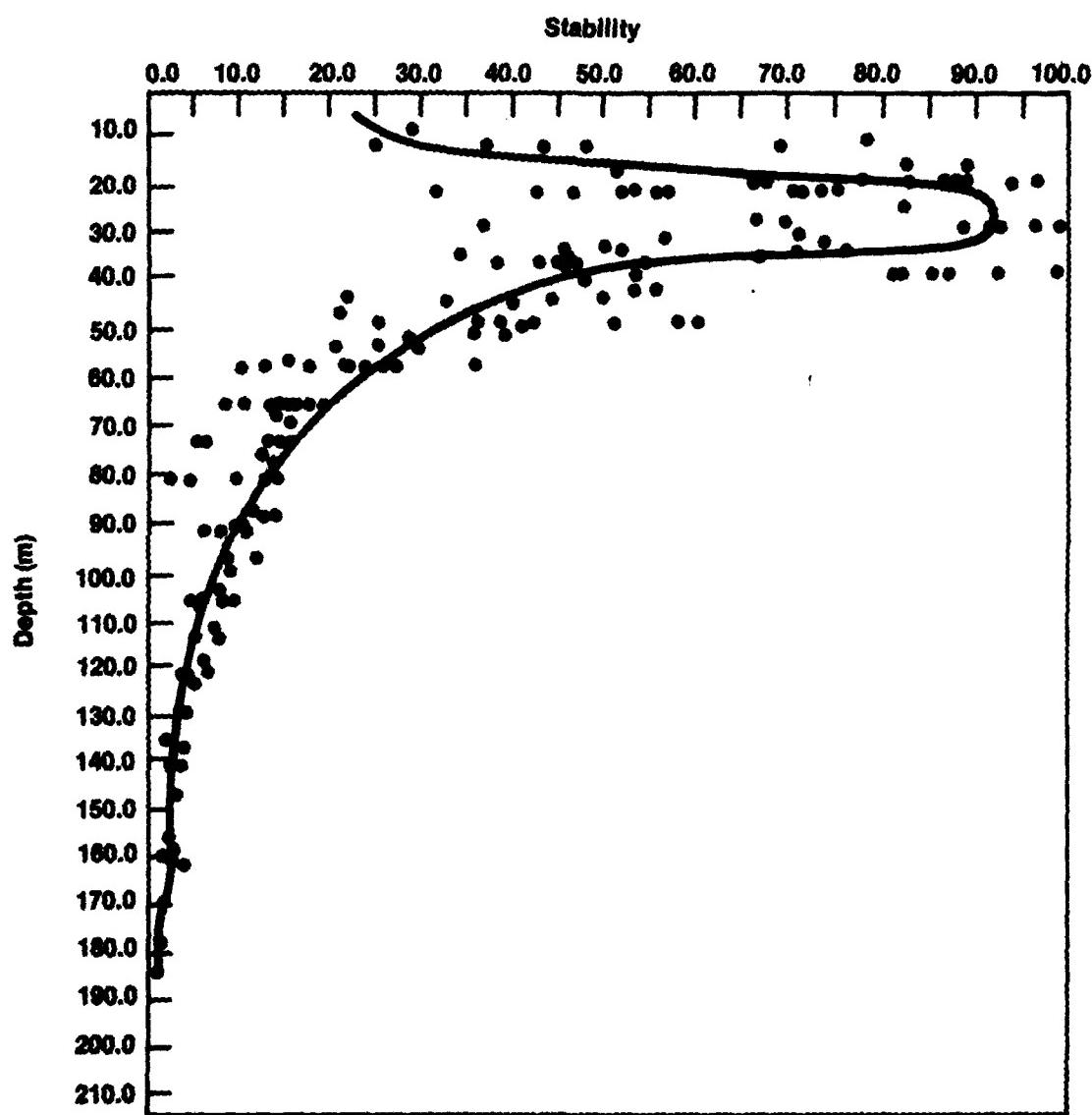


Figure 60.--Mean summer stability index profile, Gulf of Maine (after Godshall et. al., 1980).

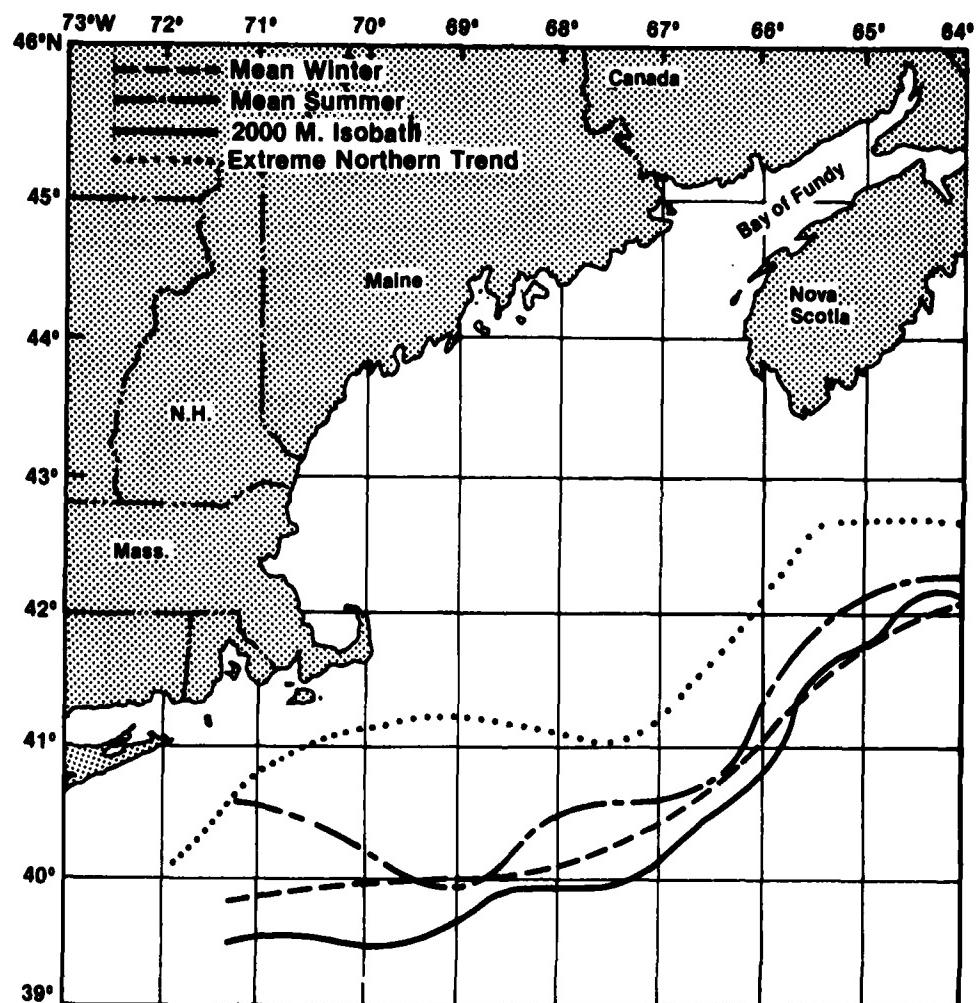
### 3.8 Ocean Fronts, Meanders and Eddies

The watermass boundary (front) between coastal (shelf) water and slope water occurs at a sharp front located at about the 2000 meter isobath (Figure 61). Figure 62 represents a typical vertical cross-section through this frontal zone across the study region. Surface temperature differences across the front are about 2 C to 4 C, to a maximum of 8 C. Salinity differences are on the order of 1 to 2 ppt over 10-15 kilometers horizontally, and 20 to 40 m vertically. Meanders of the frontal surface of  $\pm 75$  kilometers (toward land or sea) have been observed to propagate southwest (the opposite of Gulf Stream meanders). The strong horizontal stratification and velocity shears in the frontal region would tend to trap an oil spill in this region.

Anticyclonic eddies that break off from the Gulf Stream are an important mechanism for transferring properties (heat, momentum, salt) from the Gulf Stream to the slope water. They form from large in-shore Gulf Stream meanders that detaches to produce a clockwise vortex. Strong currents and stratification also make eddy location important in the predictions of oil spill advection. Oil spilled on the southern portion of the eddy will travel toward the west; oil spilled on the northern portion of the eddy will flow toward the east.

The meanders of the Gulf Stream occasionally become elongated and form separate rings that retain their identity for long periods of time. The rings, which break off in the Sargasso Sea, rotate in the counterclockwise sense and contain slope water which at any depth is colder than the surrounding Sargasso Sea water. Therefore, they are called cyclonic or cold-core rings or eddies. Conversely, those which break off in the slope water rotate clockwise and contain water that is anomalously warmer; they are known as anti-cyclonic or warm-core rings or eddies (Figures 63-64). One of the principal mechanisms producing anomalous conditions in the water mass over Georges Bank is the passage of warm-core Gulf Stream eddies along its outer edges (NMFS, 1980).

The occurrence and movement of warm-core rings are being documented by both satellite imagery and ART aircraft flights. The monthly "Gulfstream" summaries now regularly show their shape and position. Most warm-core rings appear to develop in the region of large Gulf Stream meanders east of 66 W, but some are formed in the western slope water. At the same time that the ring is moving, it is also rotating with speeds near the outer edge ranging up to about 1 kt (52 cm/sec). From satellite observations, it appears that the rotating rings entrain surface shelf water along the shelf/slope boundary and draw it out into the slope-water in long, narrow filaments (Morgan and Bishop, 1977). Warm-core rings begin to decay shortly after formation; first the surface cools to the temperature of the surrounding slope water, then the warm water begins to mix away around the circumference. The lifetime of a ring is estimated at 6 months to a year, but the ring may appear to be re-absorbed by the Gulf Stream before it loses its identity. The diameters of these eddies vary from about 100 to 200 km at the surface. There is a tendency for an eddy to decrease somewhat in size once it crosses 70°W.



**Figure 61.--Normal and extreme shelf/slope water frontal positions in winter and summer compared to 2000 meter isobath. Extreme southern shelf/slope water position is south of 39 N Latitude. (Godshall et. al., 1980).**

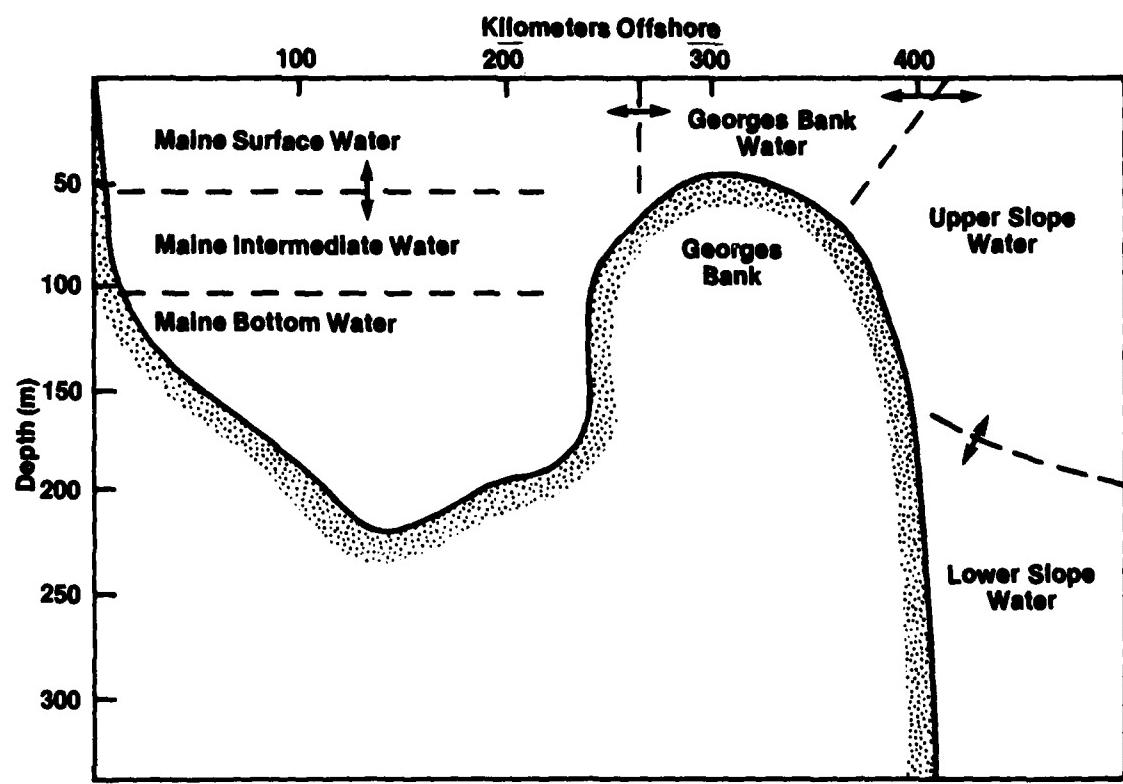


Figure 62.--Water mass schematic of the Gulf of Maine (Hopkins and Garfield, 1977).

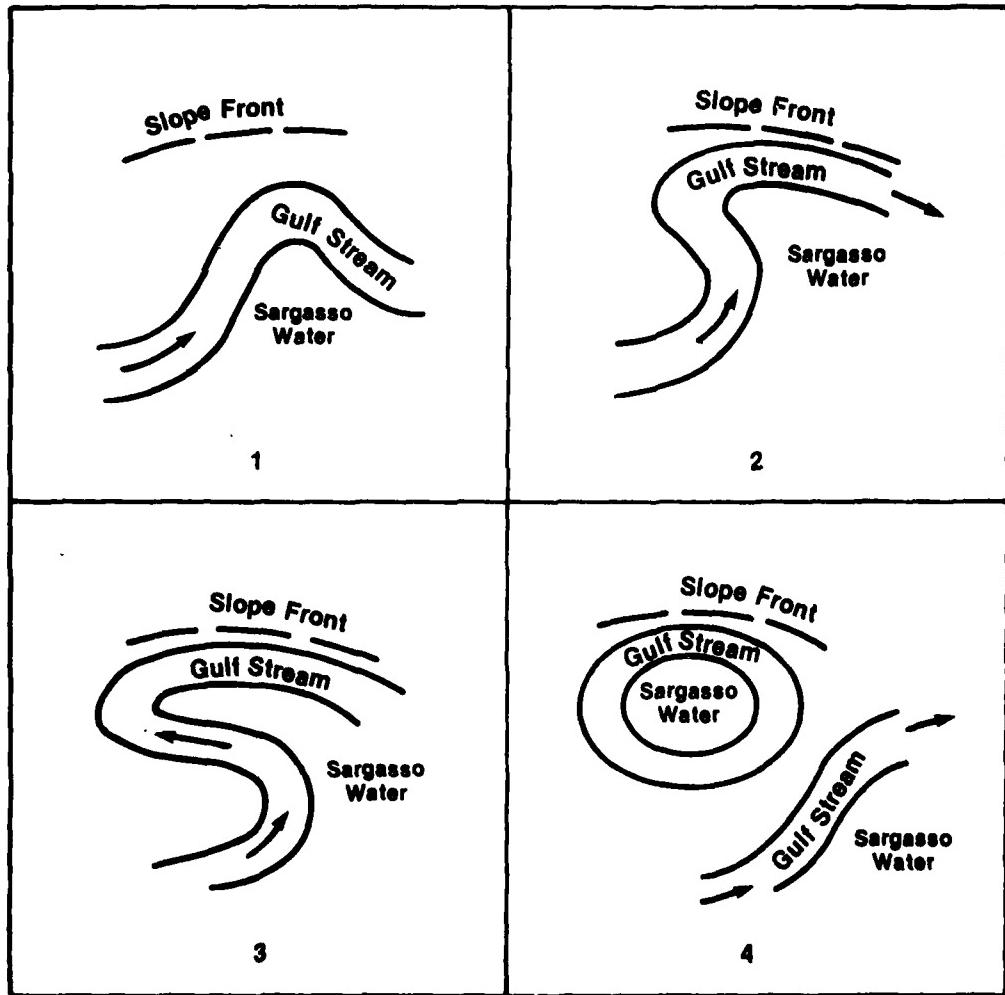
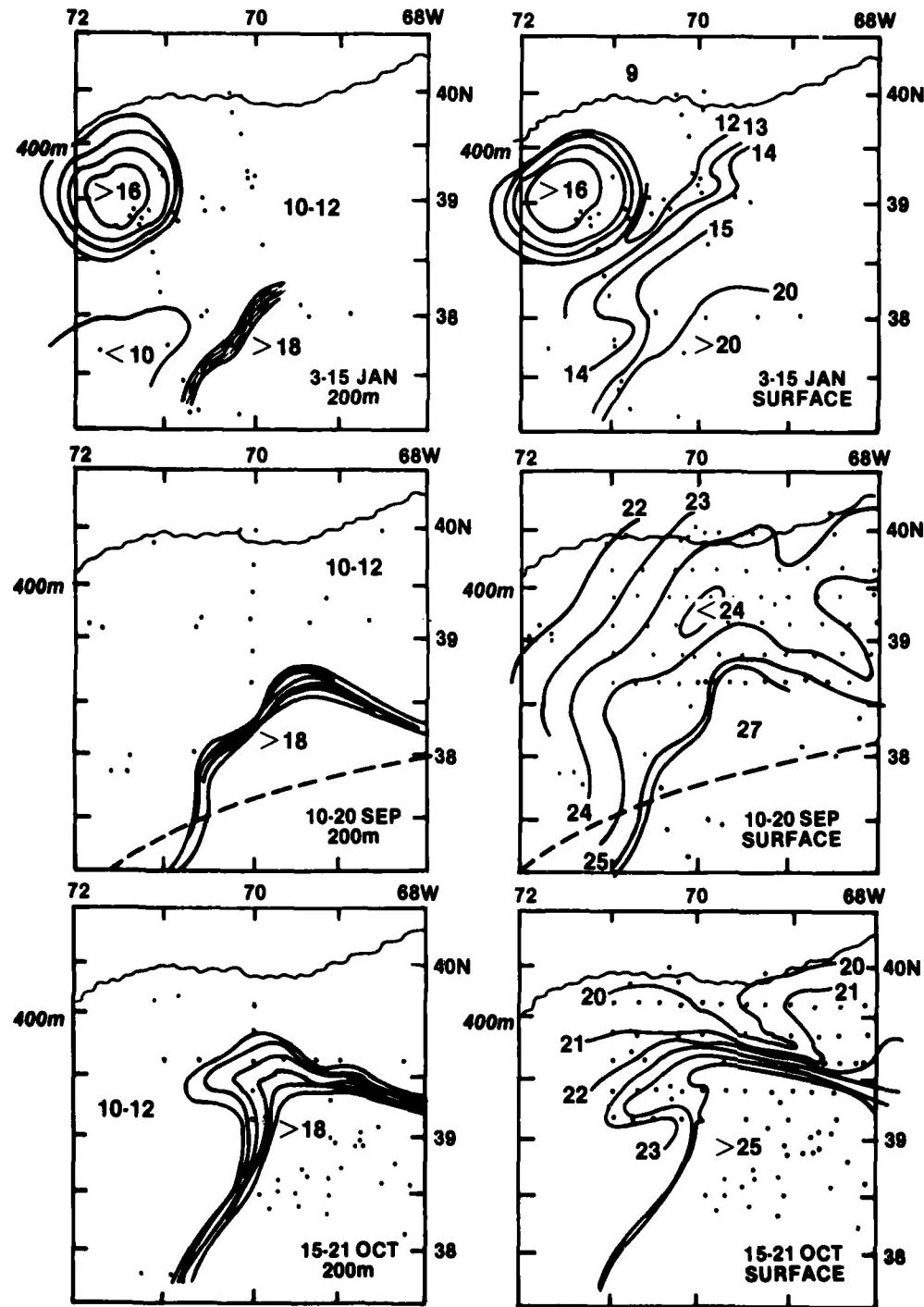


Figure 63.--Anti-cyclonic (warm-core) Gulf Stream Eddy formation.



**Figure 64.--**Observed development of a warm core ring (eddy) (after Wright, 1976).

### 3.9 Mean Coastal Currents

The "permanent" average flow in the coastal region of the Gulf of Maine/Georges Bank is variable. Studies by Bumpus (1965) of the permanent flow inshore of the 100 - meter isobath indicate a mean flow on the order of (0.1 kt, 5.2 cm/sec) for the area. Bottom currents appear to be much weaker (0.008-0.02 kt; 0.4-1.0 cm/sec) than surface currents and flow south and southwest. A seasonal fluctuation in the permanent coastal current results from variation in wind stress and runoff.

Seasonal surface current vectors based on a subjective analysis of available data are presented in Figures 65 to 68. They clearly show the well-documented mean southwest coastal flow that turns around Cape Cod, and a northward flow seaward of the 200 meter isobath off the continental shelf. The typical mean speed is about 0.1 kt (5.2 cm/sec).

One important feature of the flow is the strong seasonal variability, especially near the mouths of estuaries. In winter the primary driving force is the northwest wind stress, while in summer it is the cross-shelf pressure gradient generated by the outflow of low-salinity water from the mouths of estuaries.

### 3.10 Calculated Climatological Relative Risk Ellipses for the Gulf of Maine/Georges Bank Region

To get a first-order estimate of the most probable path an oil spill will take, a climatological approach was used. This technique is based on the assumption that advection of the oil slick by wind-driven and permanent currents are the most important factors over long periods. With this approach, wind drift was given as 3 percent of the hourly wind speed directed 15° to the right of the wind. Permanent currents are taken from Section 3.9. Trajectories were started from a hypothetical spill site and tracked on an area geographic chart by computer for 10 nautical-mile by 10 nautical-mile areas. The climatological wind records for Brunswick, Maine and Nantucket Memorial Airport were obtained from the National Climatic Center at Asheville, N.C., and were used to develop thousands of trajectories for the four seasons. The resulting area impacts were divided by the total trajectories, and relative risk ellipses were thus formed.

These ellipses, Figures 69-72, are appropriate for the section of the study region specified. The winter ellipses mirror the statistics of the wind field since the winter mean wind is toward the southeast and wind variability is relatively low. Thus, these risk calculations show a northwest/southeast elliptical distribution. In the summer, when the mean wind is toward the northeast and variability is high, a more circular distribution is calculated. The use of these ellipses in conjunction with the resource charts of environmentally critical areas is a technique that can be employed to estimate spill risk from selected spill sites. Such a use is consistent with pre-spill contingency planning.

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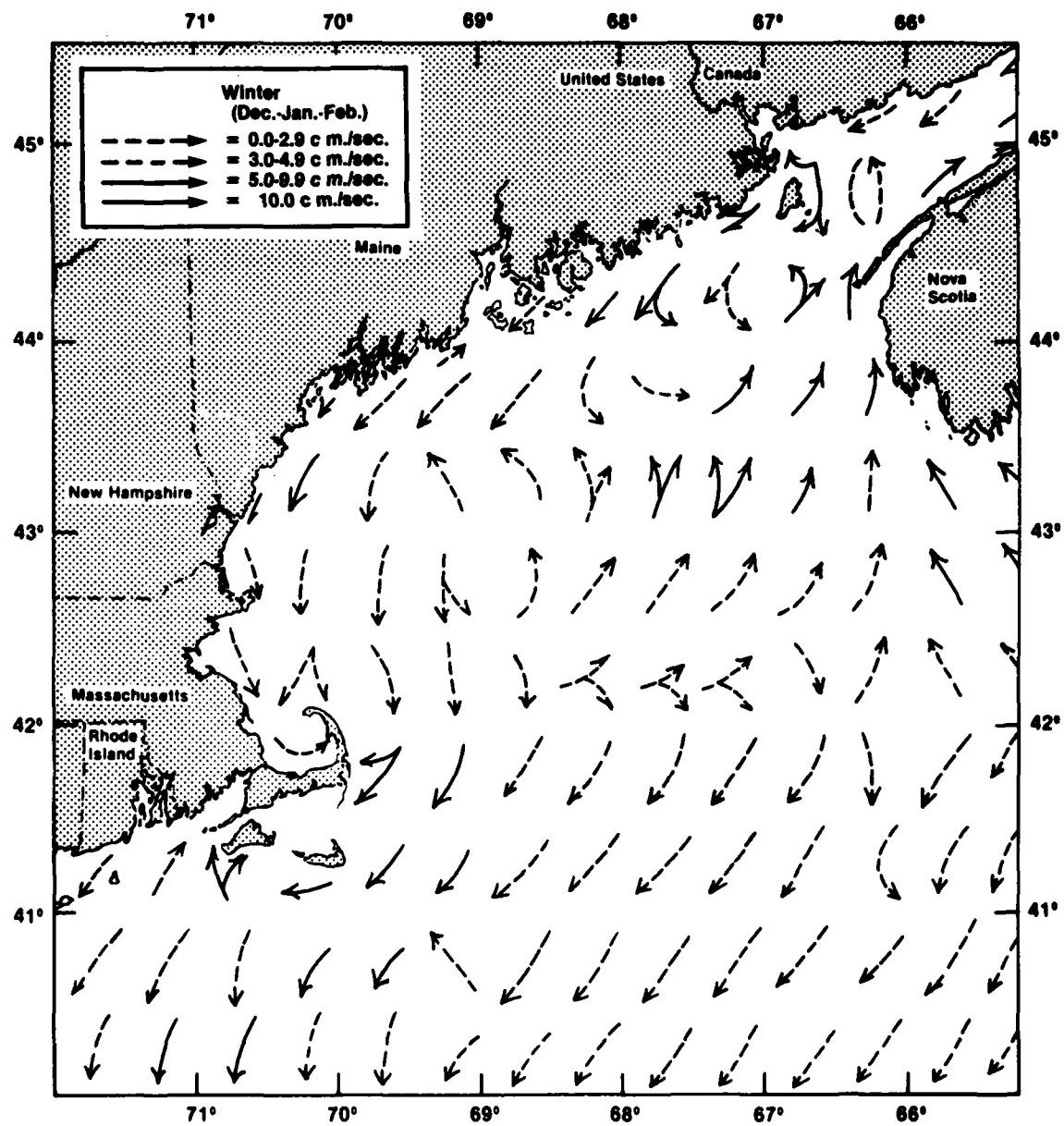


Figure 65.--Subjective Analysis of winter mean current vectors in cm/sec.

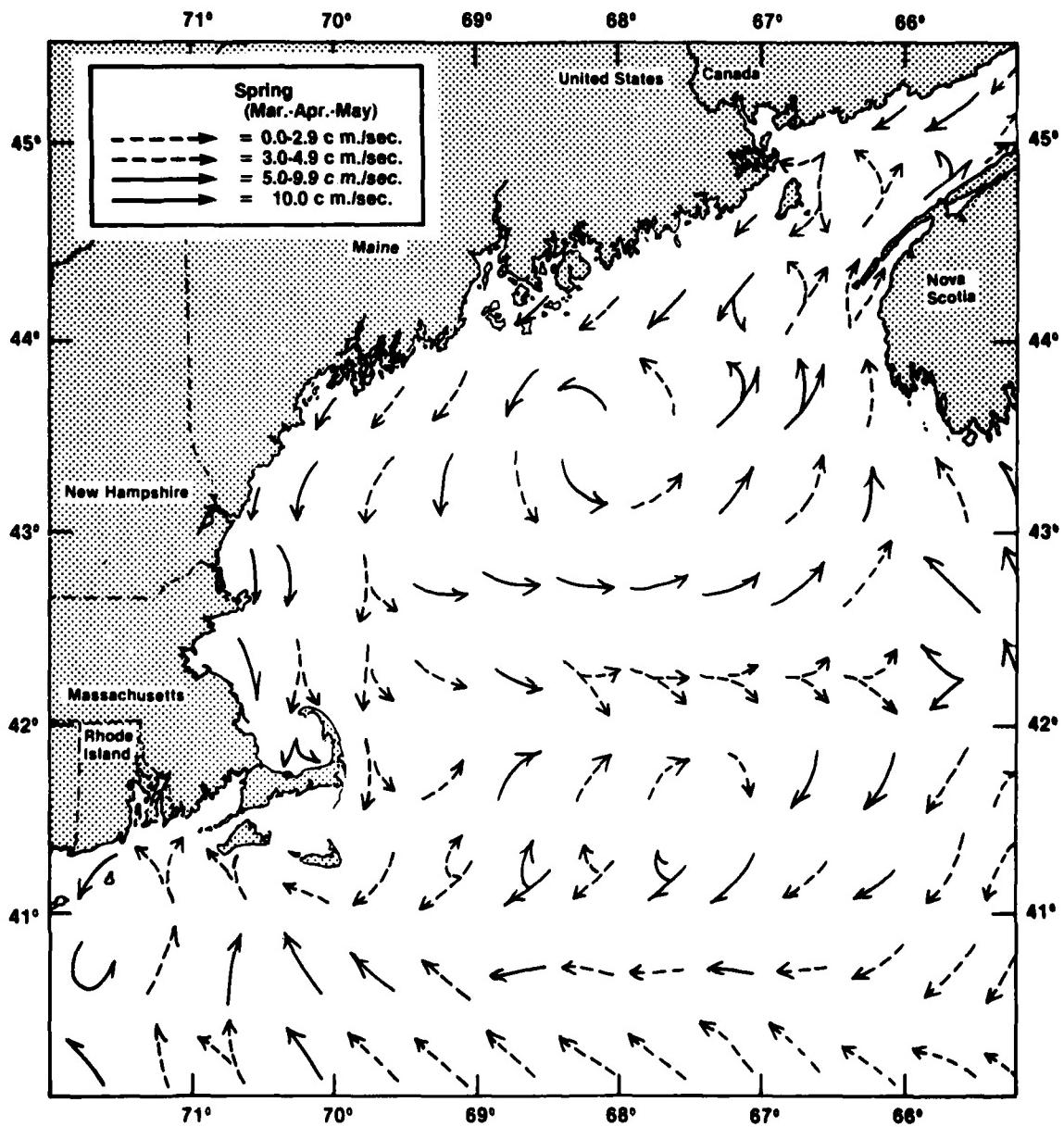


Figure 66.--Subjective Analysis of spring mean current vectors in cm/sec.

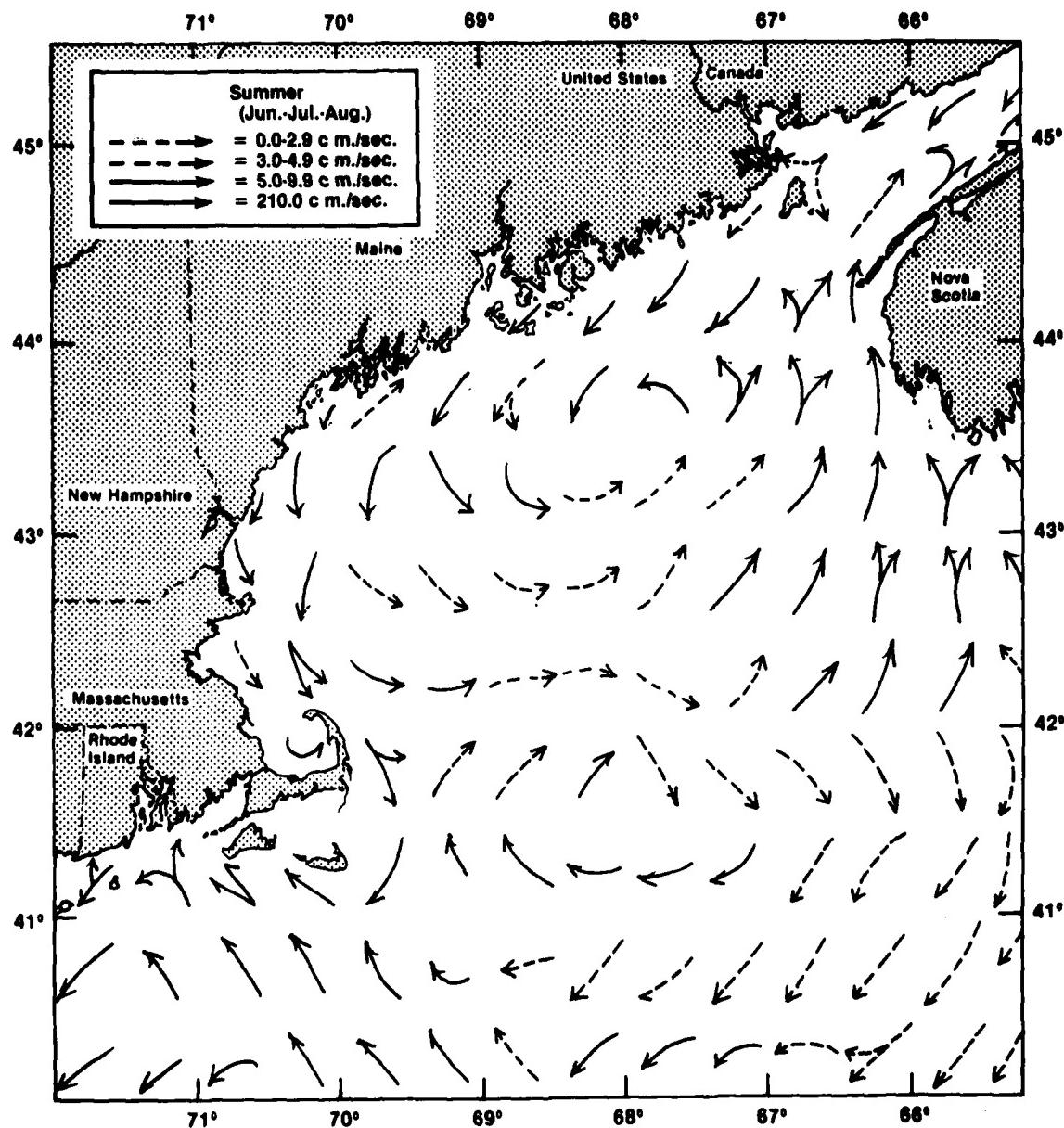


Figure 67.--Subjective Analysis of summer mean current vectors in cm/sec.

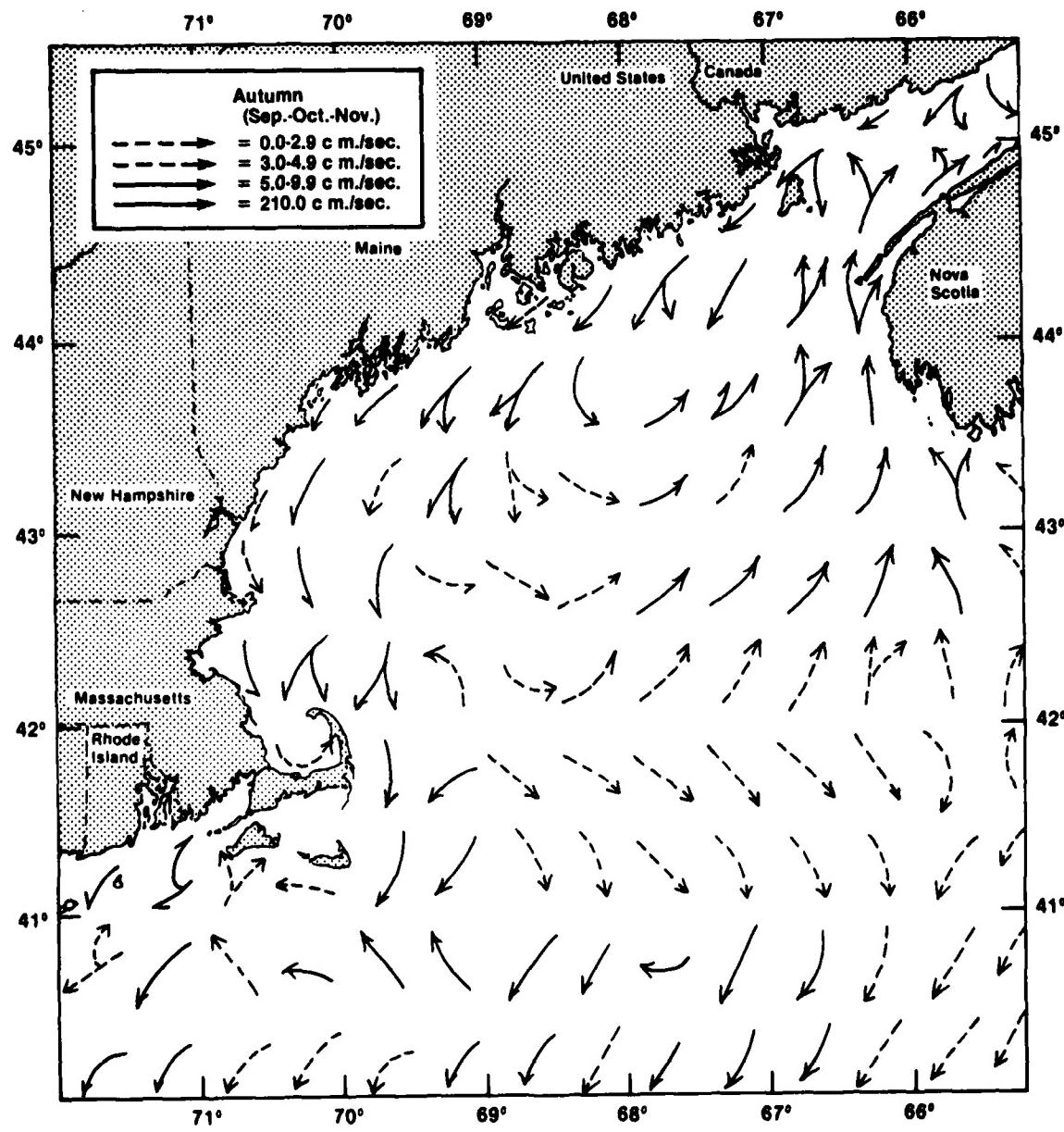
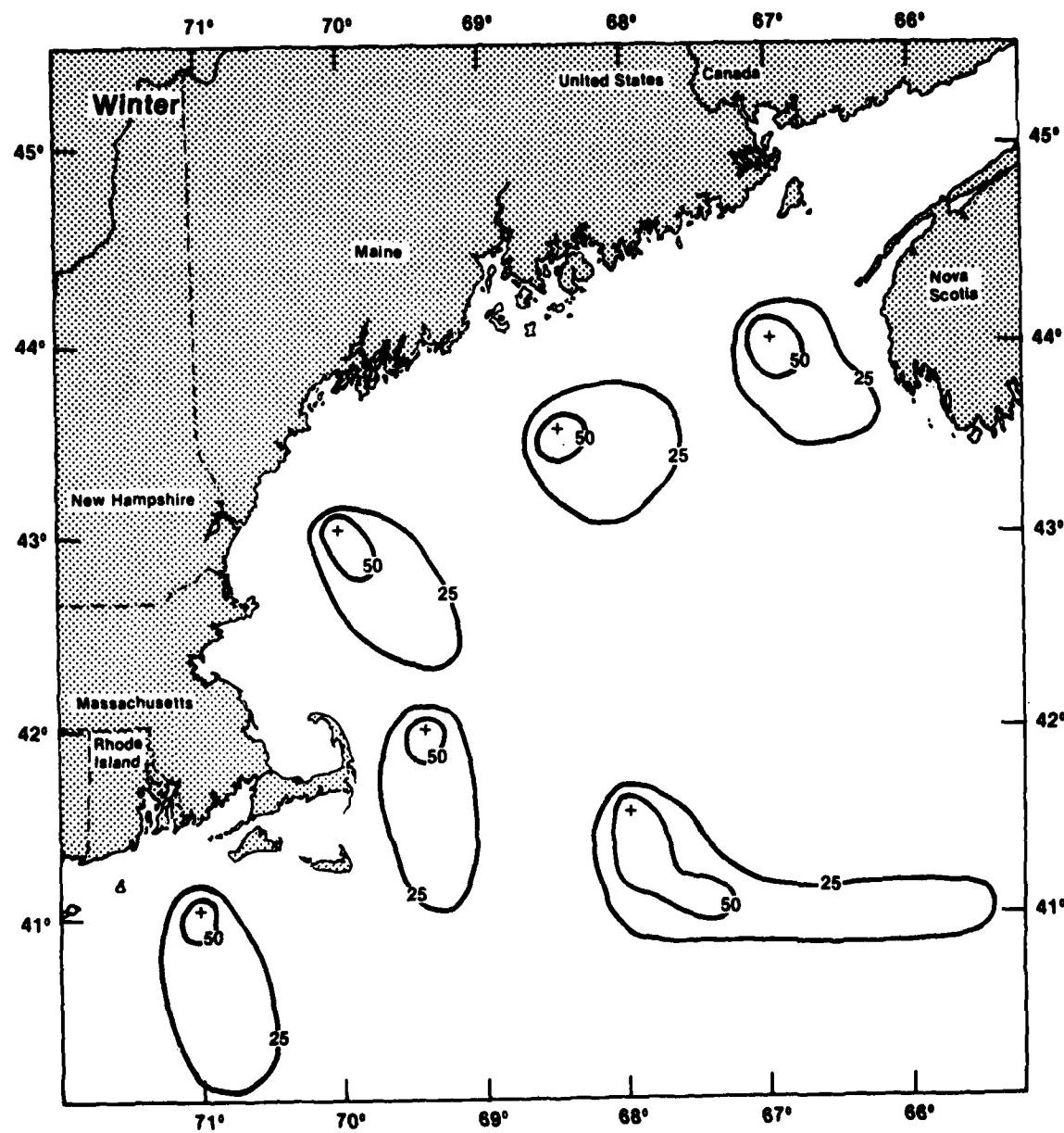


Figure 68.--Subjective Analysis of autumn mean current vectors in cm/sec.



**Figure 69.--Relative Risk Ellipses (Winter).**

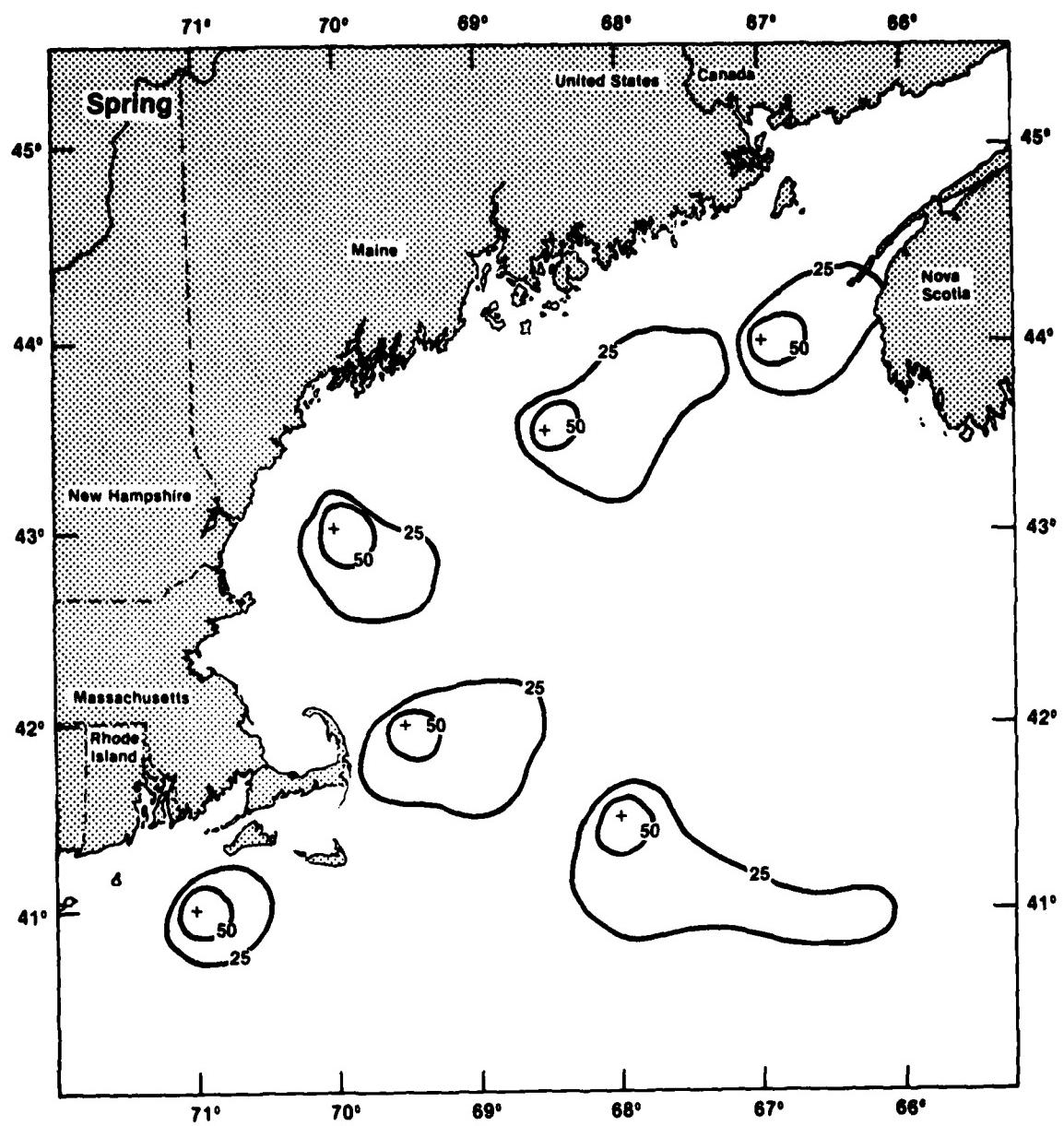


Figure 70.--Relative Risk Ellipses (Spring).

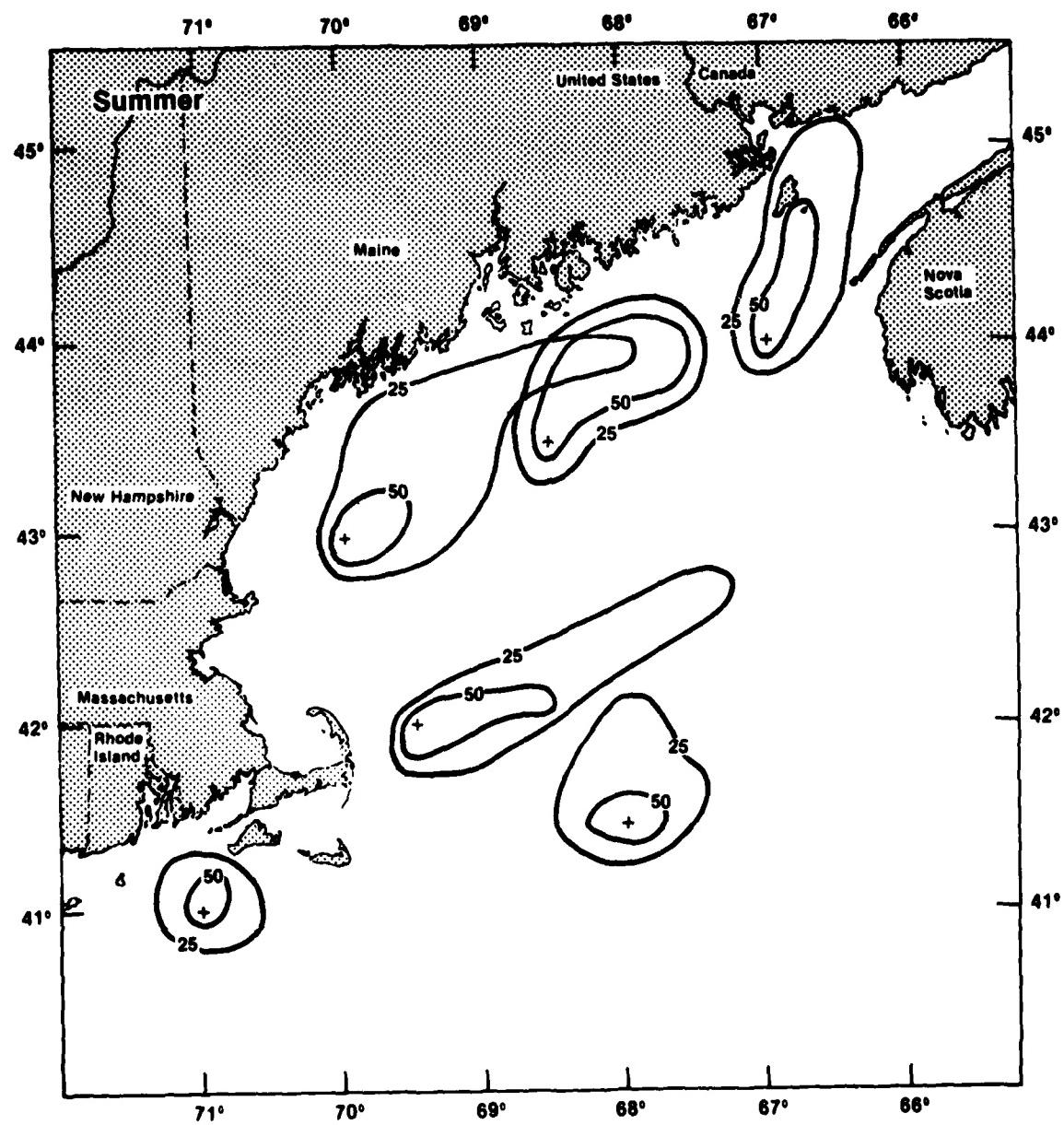


Figure 71.--Relative Risk Ellipses (Summer).

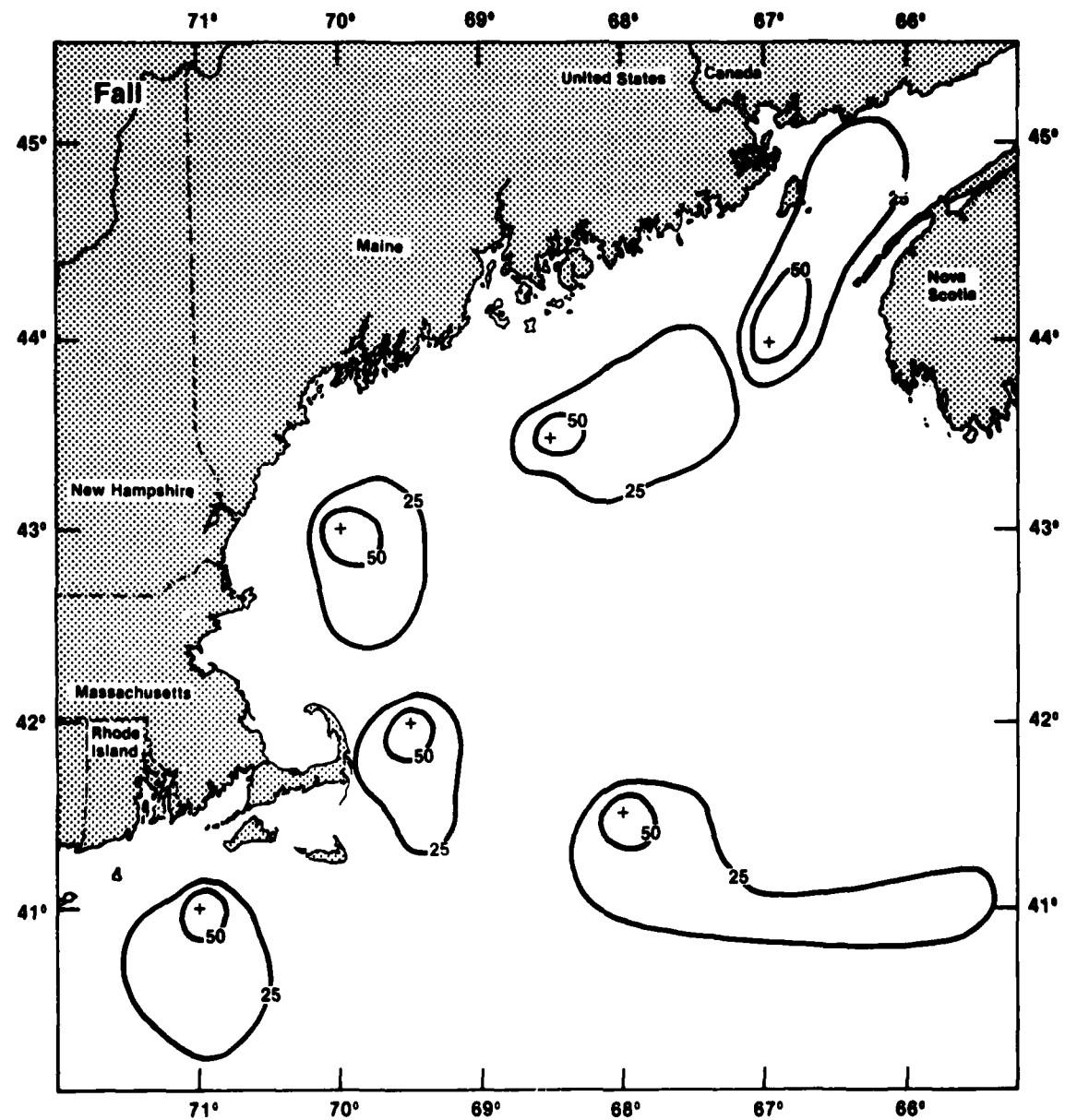


Figure 72.--Relative Risk Ellipses (Autumn).

The joint use of these charts gives a relative estimate of the impact on the environment by the planning guide user. Once the approximate spill site is known, the risk ellipse for that area can be consulted in conjunction with the resource chart(s) of interest. Thus, the relative risk (probability) of impact can be directly estimated, without complicated interpretation.

### 3.11 Biological and Recreational Resources

In the planning guide we not only consider the trajectory of the oil, but also the spatial distributions of resources which may be potentially impacted. In the biologically productive Gulf of Maine/Georges Bank region this factor is of prime concern. For this reason resources charts (Figure 73-150) have been included in the analysis.

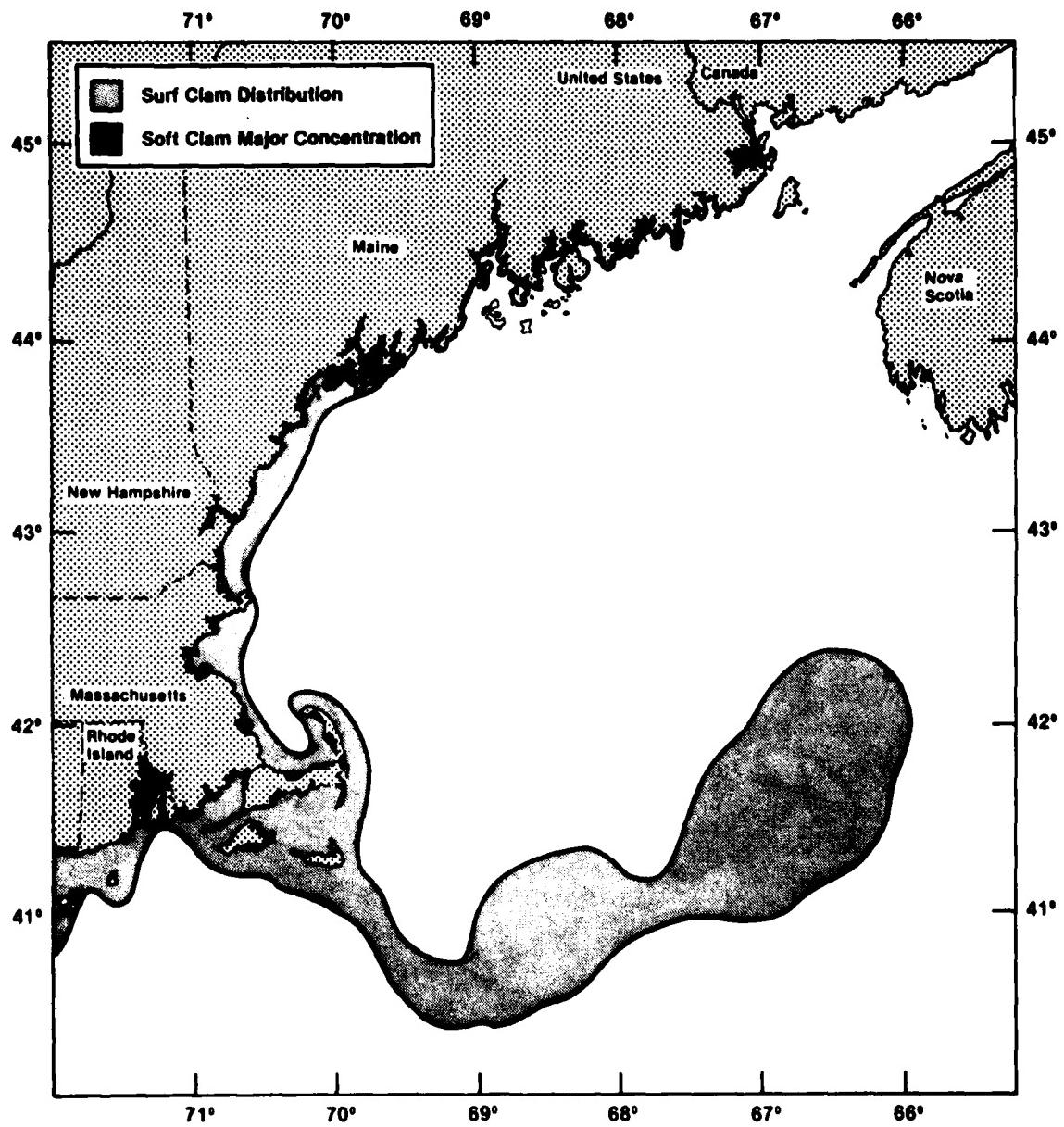


Figure 73.--Shellfish Distribution: Surf Clams and Soft Clams (after Ray and Dobbin, 1980).

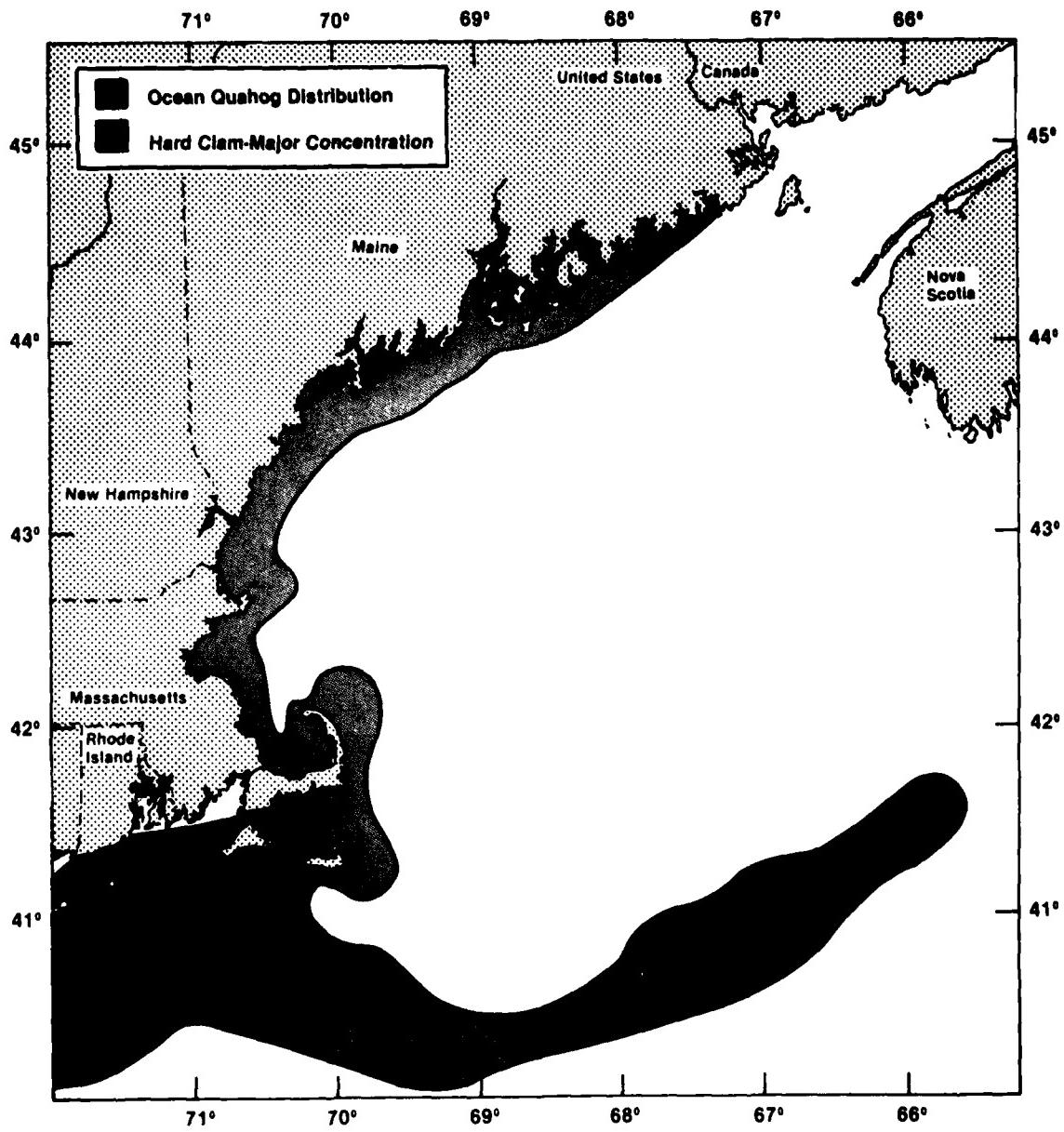


Figure 74.--Shellfish Distribution: Ocean Quahogs and Hard Clams (after Ray and Dobbin, 1980).

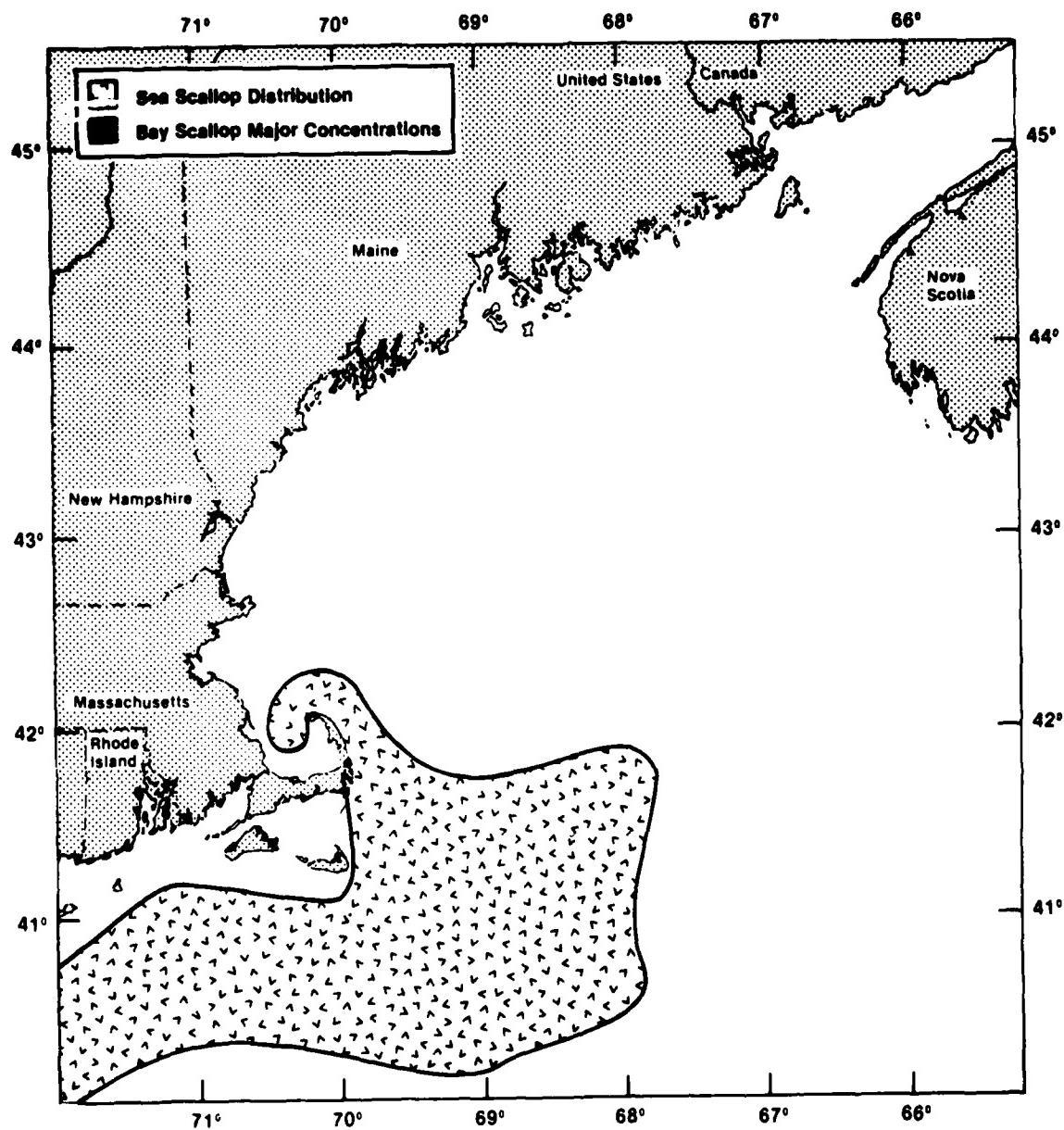


Figure 75.--Shellfish Distribution: Bay Scallops and Sea Scallops (after Ray and Dobbin, 1980).

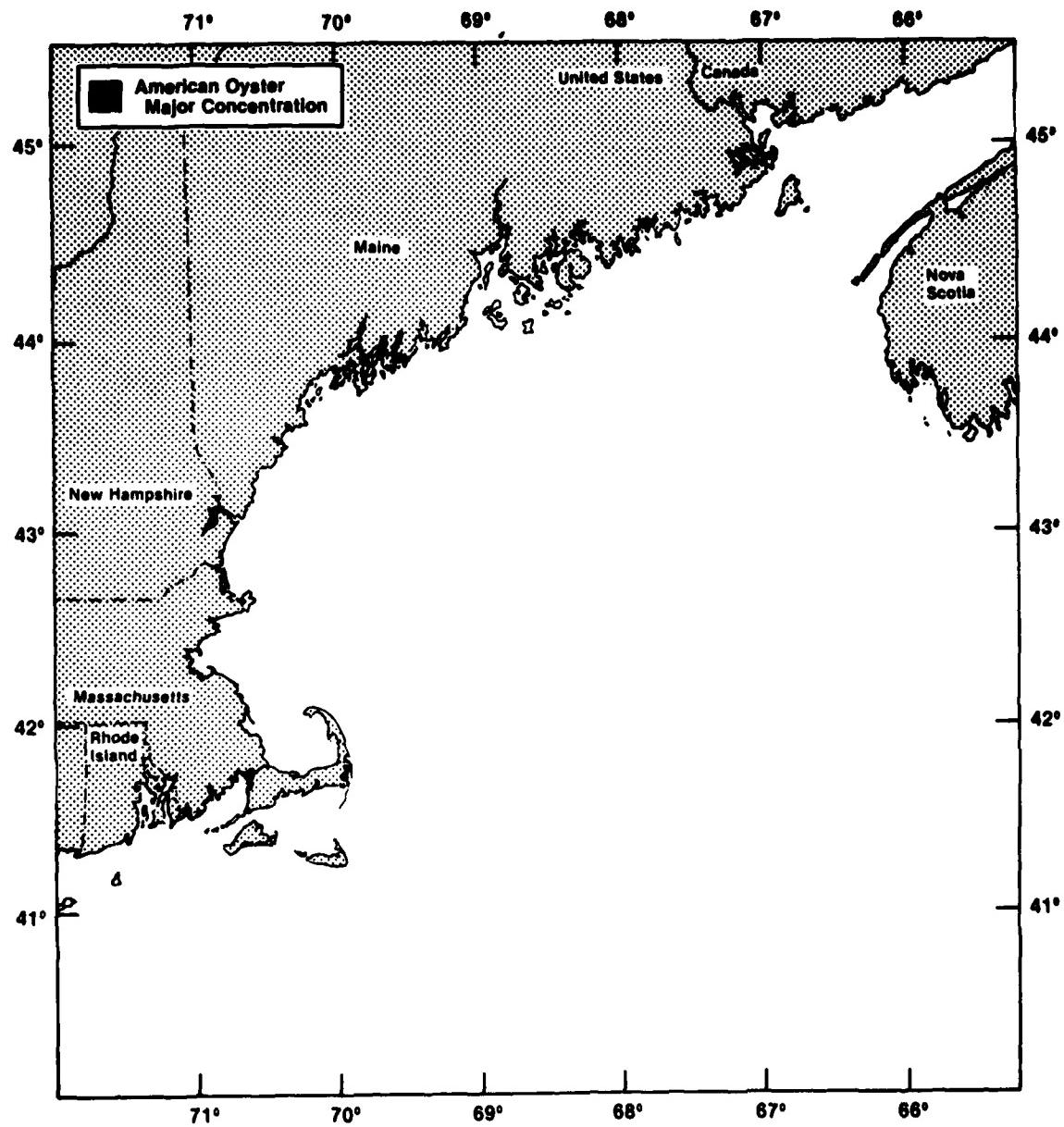


Figure 76.--Shellfish Distribution: American Oyster (after Ray and Dobbin, 1980).

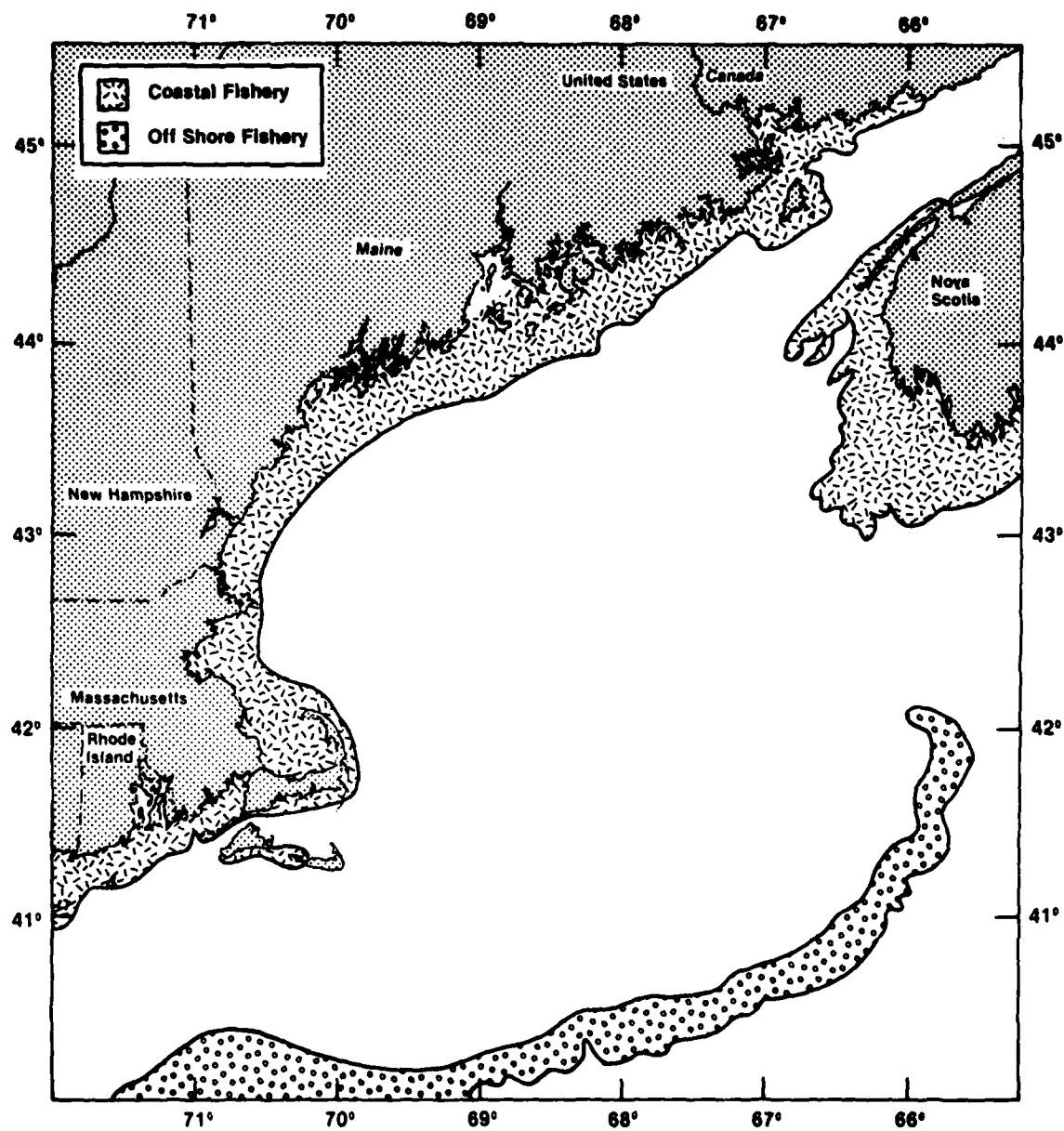


Figure 77.--Lobster Distribution (after Ray and Dobbin, 1980).

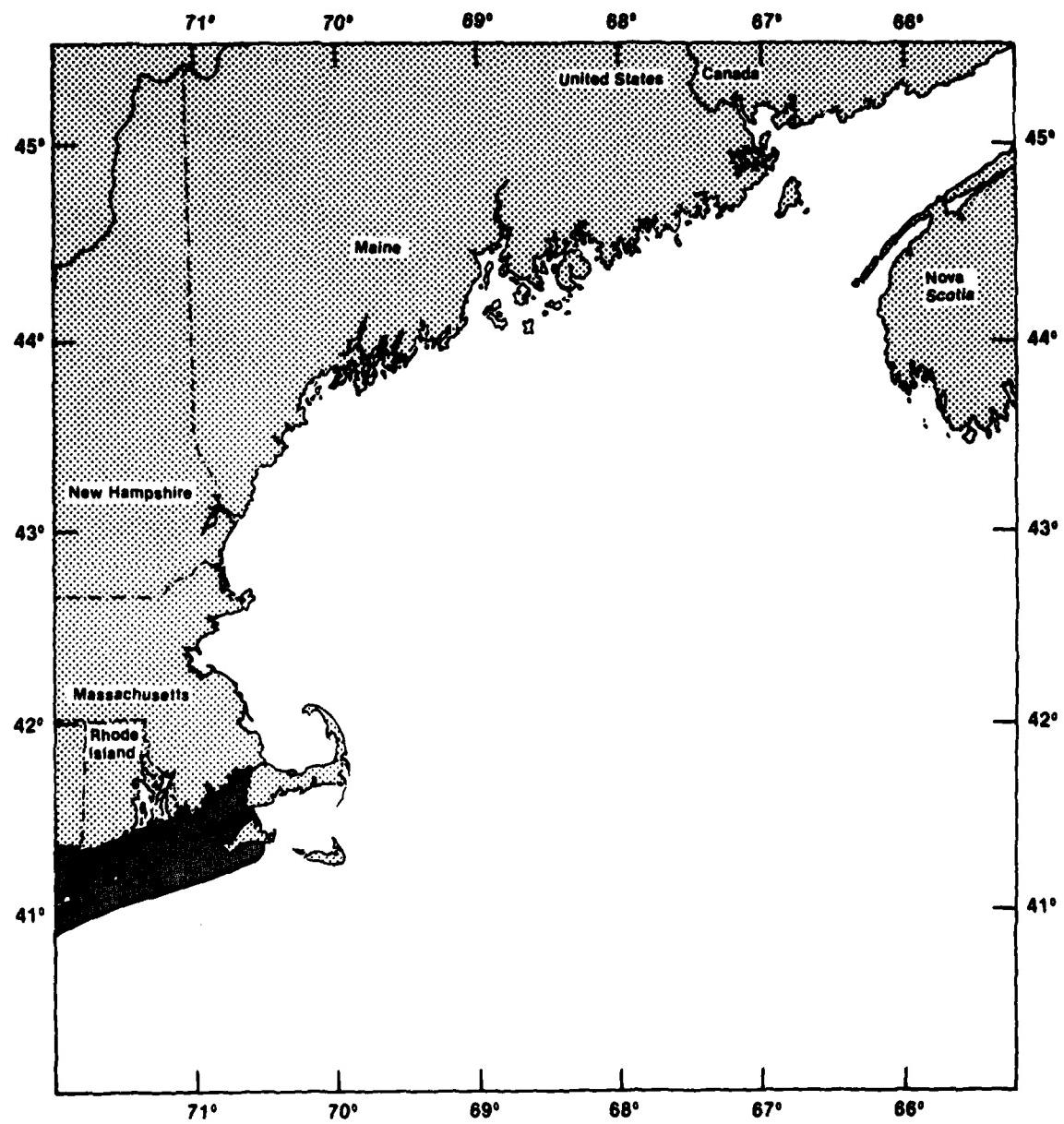


Figure 78.--Blue Crab Distribution (after Ray and Dobbin, 1980).

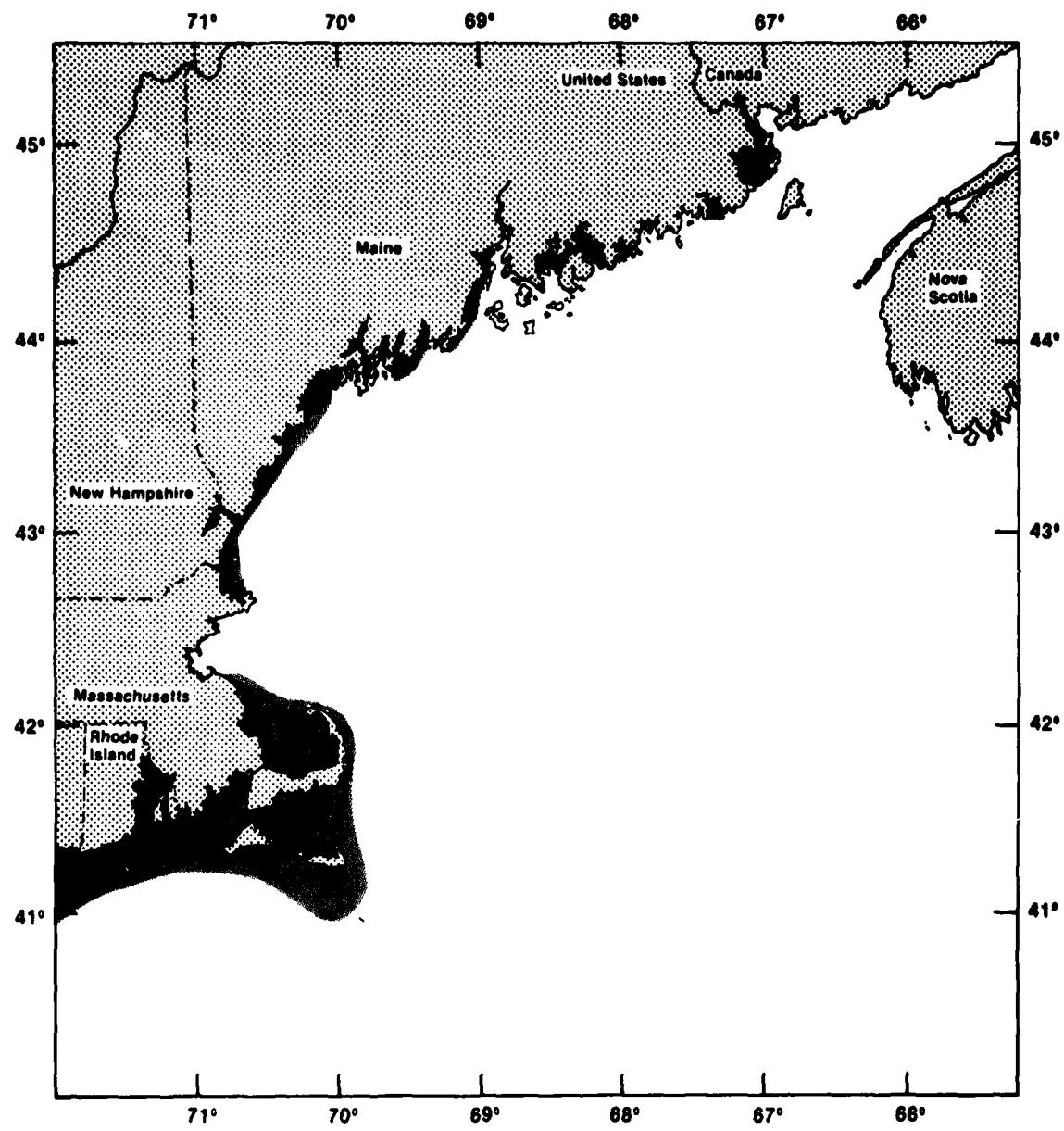
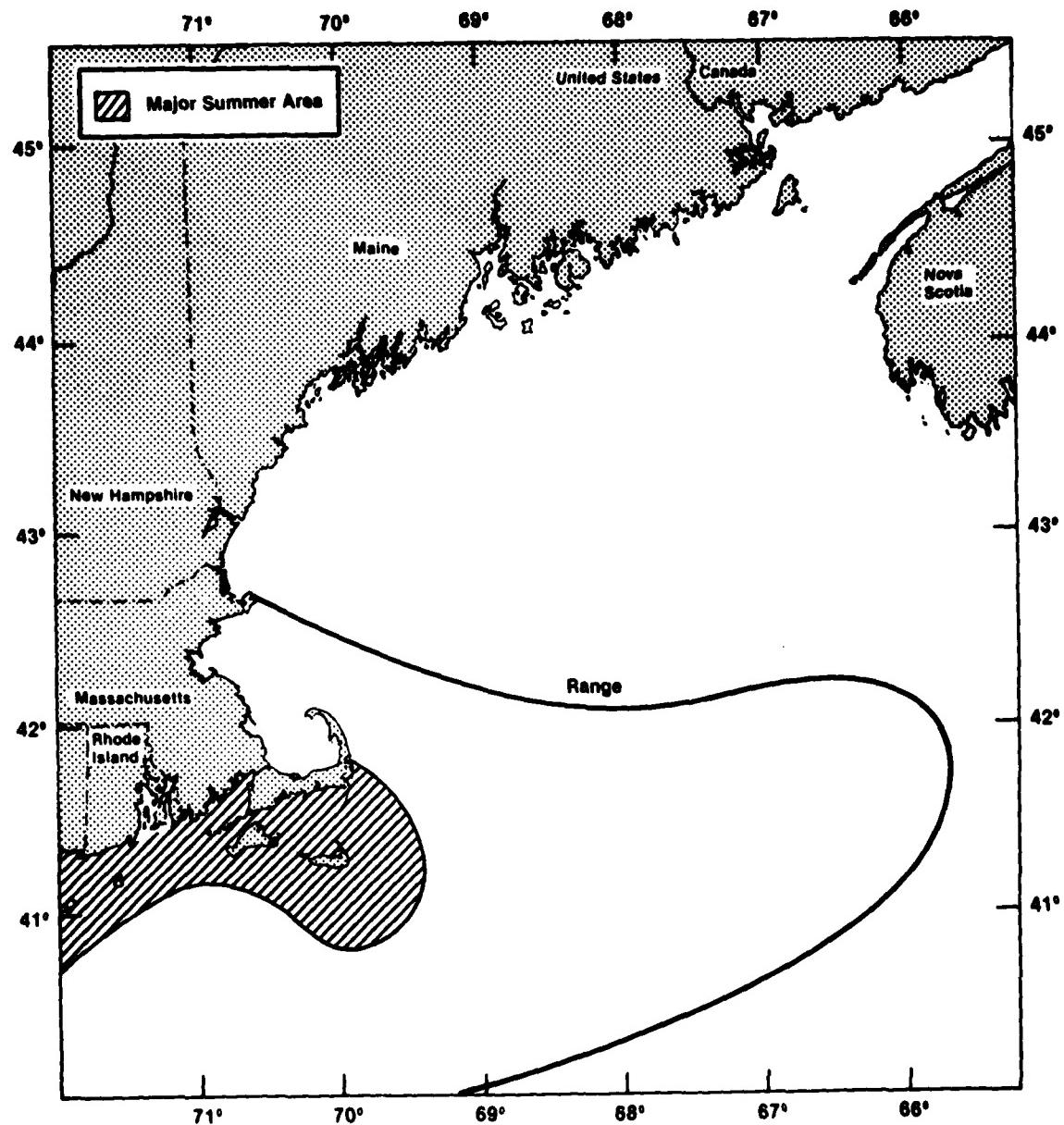


Figure 79.--Striped Bass Distribution (after Freeman and Walford, 1974).



**Figure 80.--Bluefish Distribution (after Ray and Dobbin, 1980).**

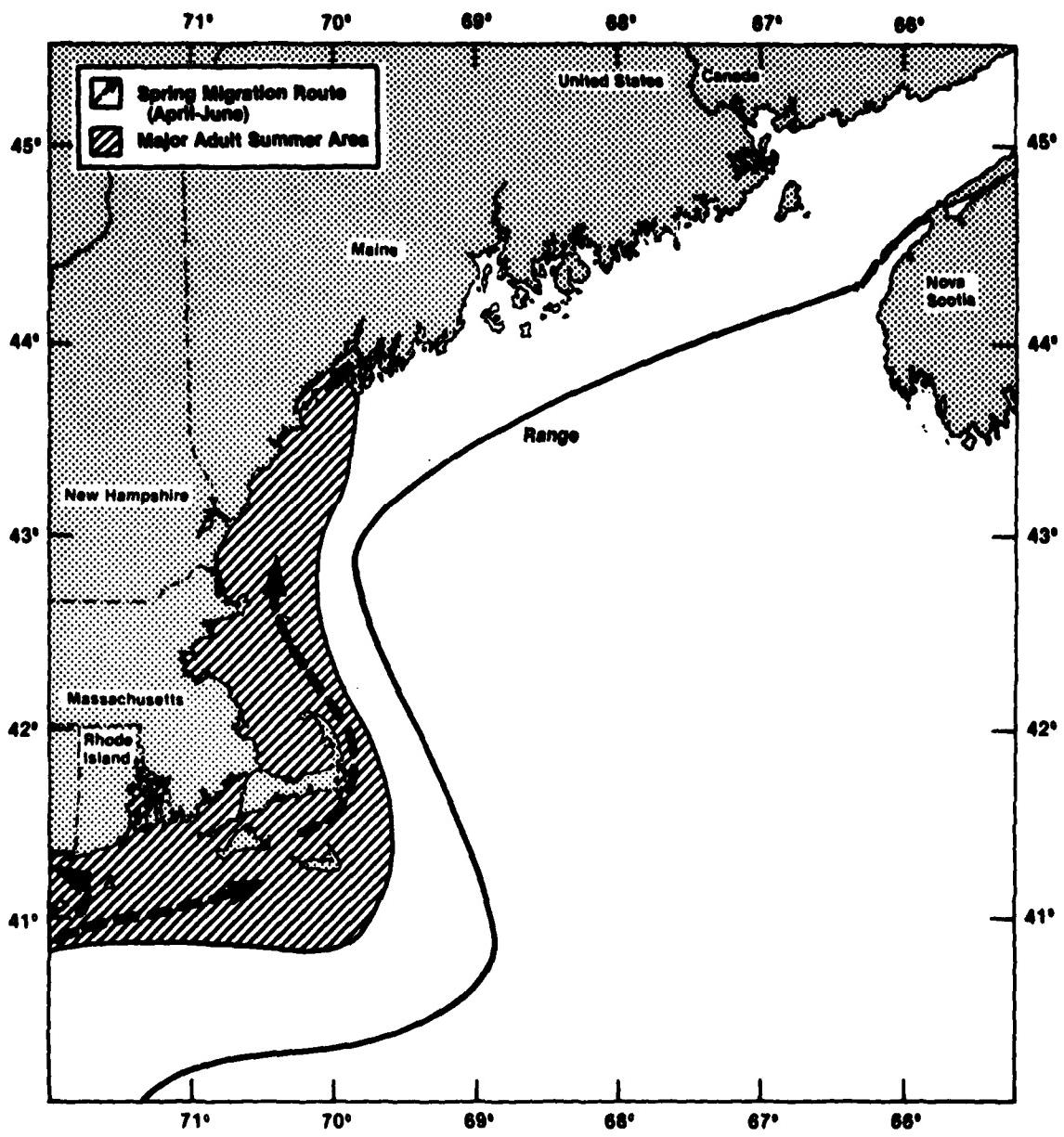
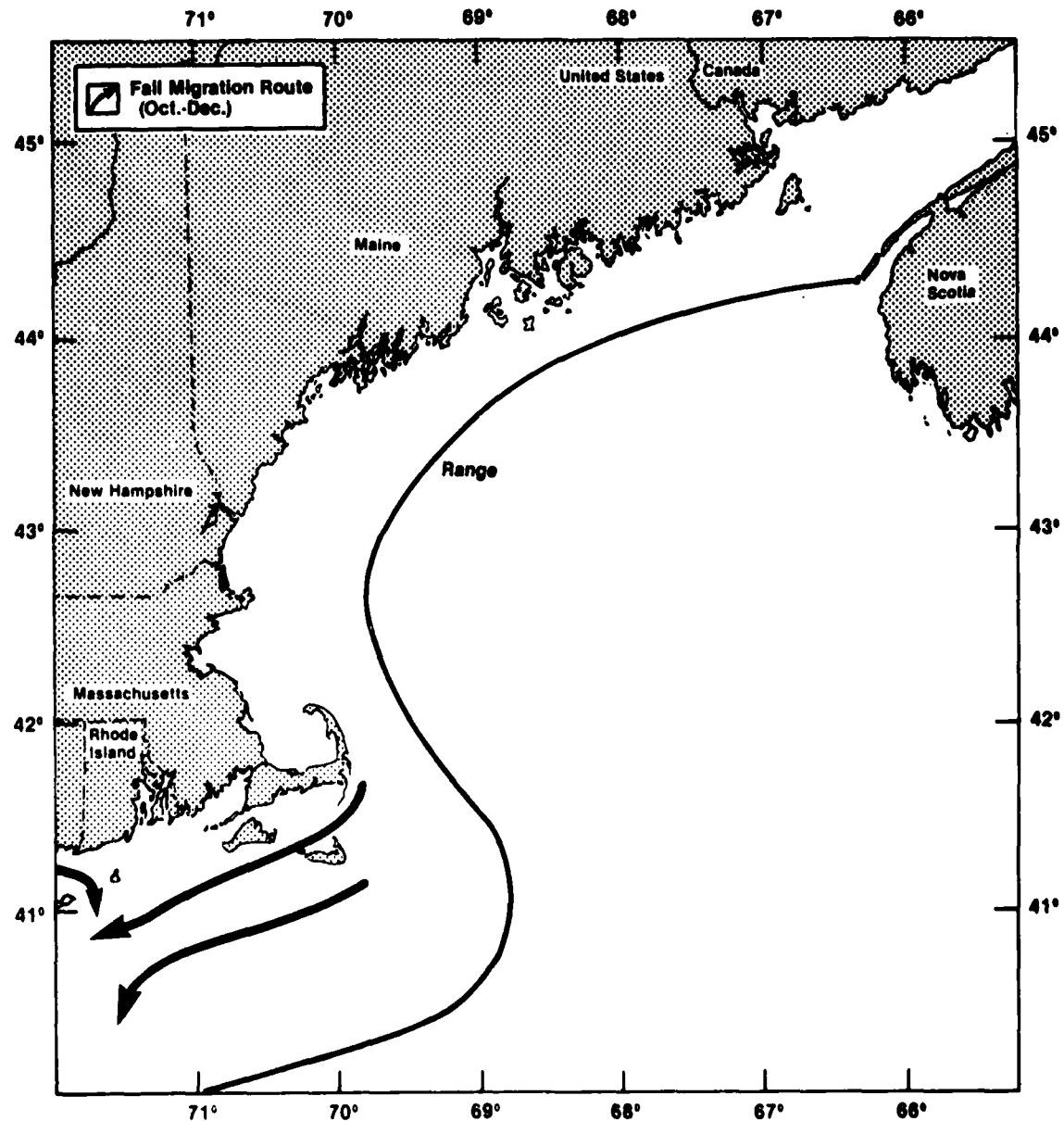


Figure 81.--Atlantic Menhaden Distribution - April to August (after Ray and Dobbin, 1980).



**Figure 82.--Atlantic Menhaden Distribution - October to March (after Ray and Dobbin, 1980).**

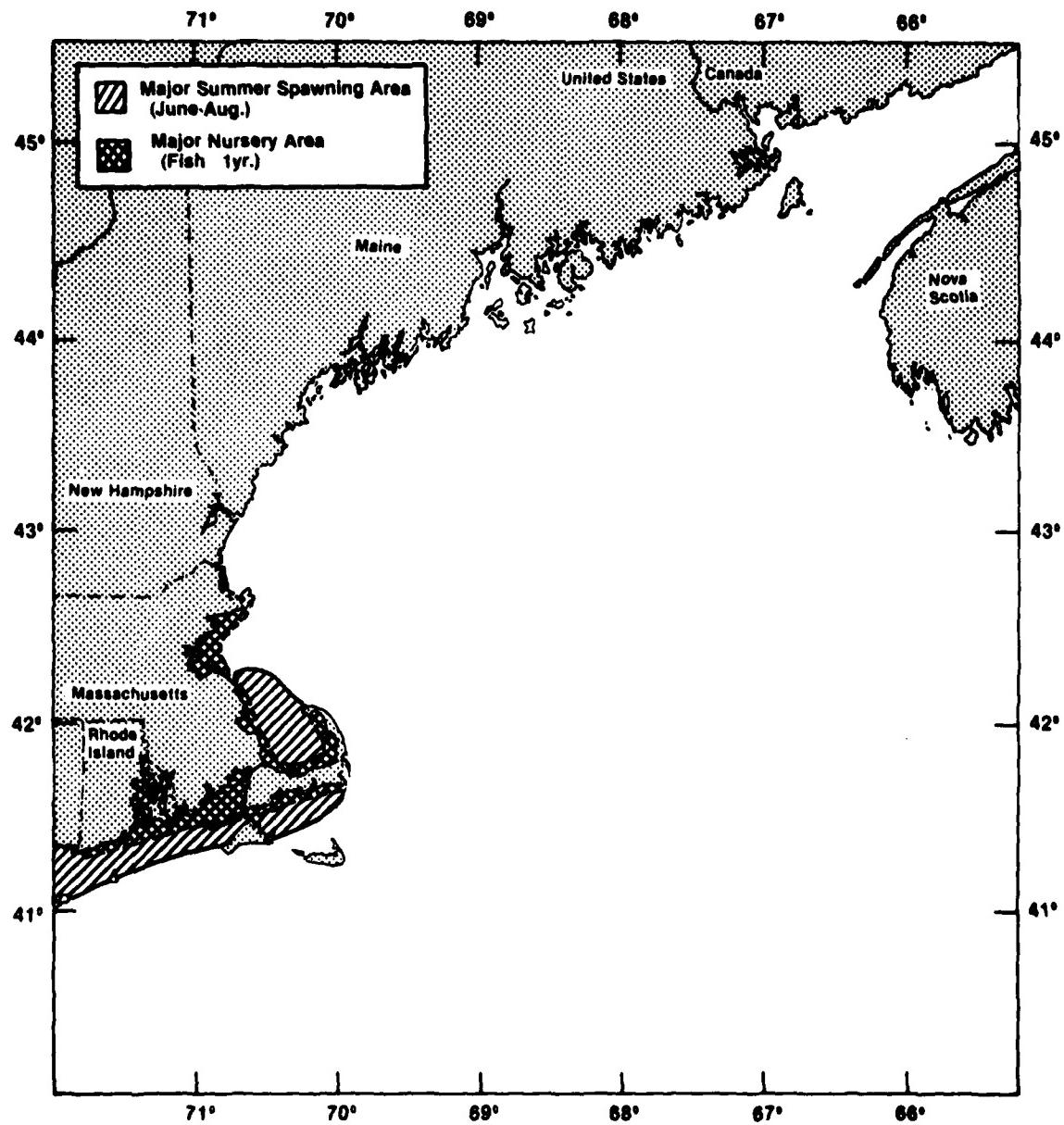


Figure 83.--Atlantic Menhaden Spawning (June-August) and Major Nursery Areas (after Ray and Dobbin, 1980).

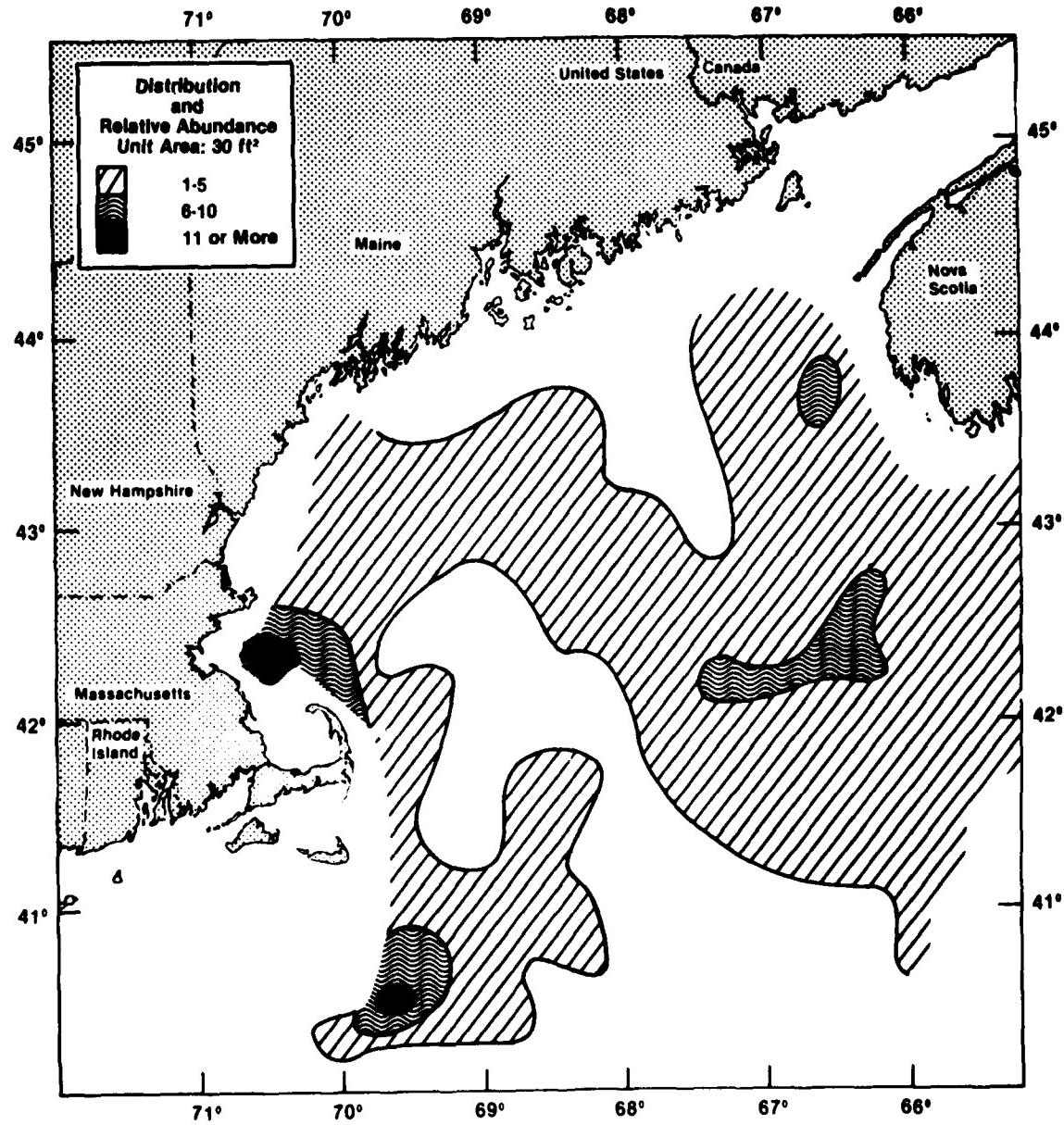


Figure 84.--Atlantic Cod Distribution (after Fritz, 1965).

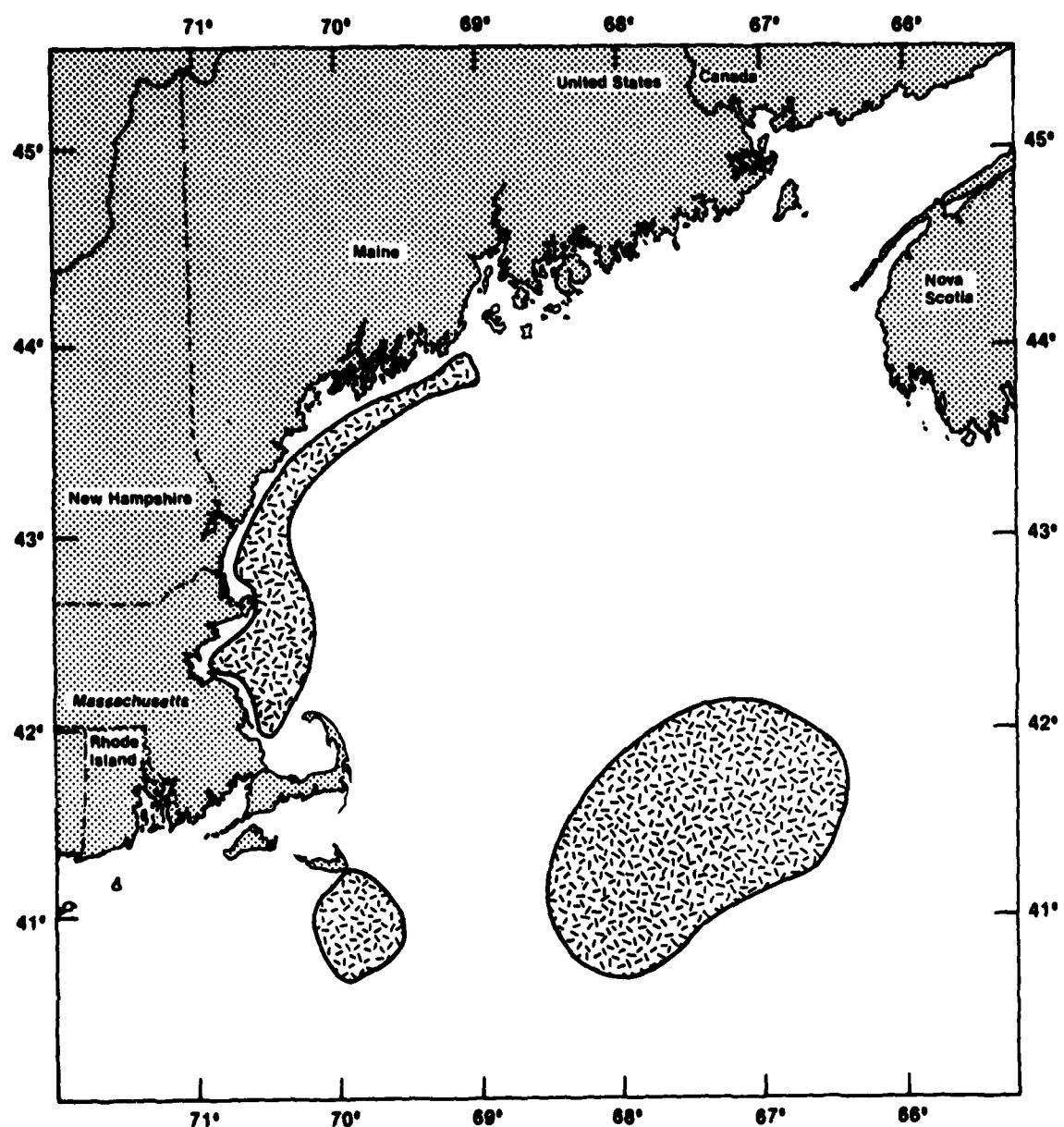


Figure 85.--Atlantic Cod Spawning Areas (January-March) (after Ray and Dobbin, 1980).

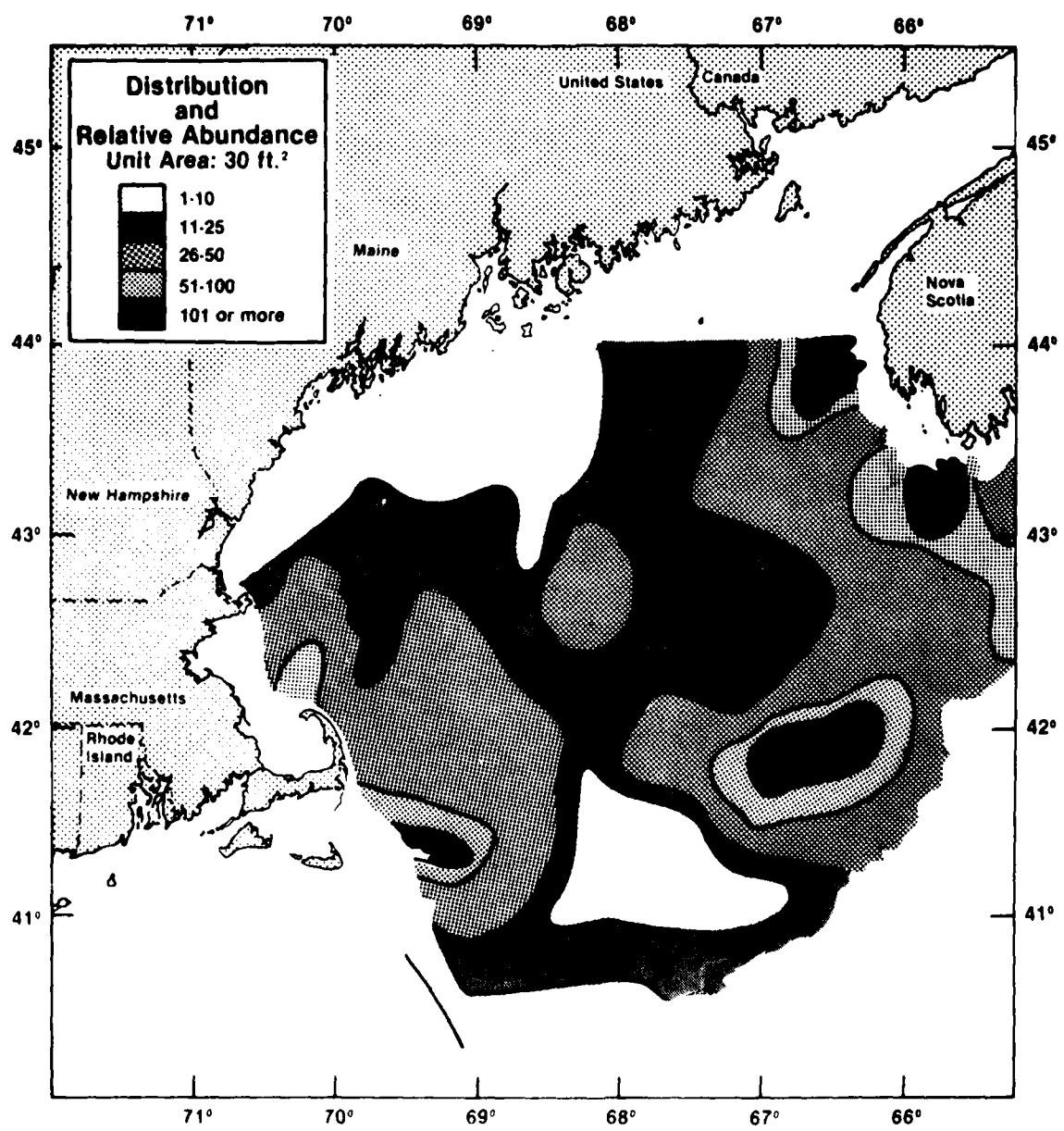


Figure 86.--Haddock Distribution (after Fritz, 1980).

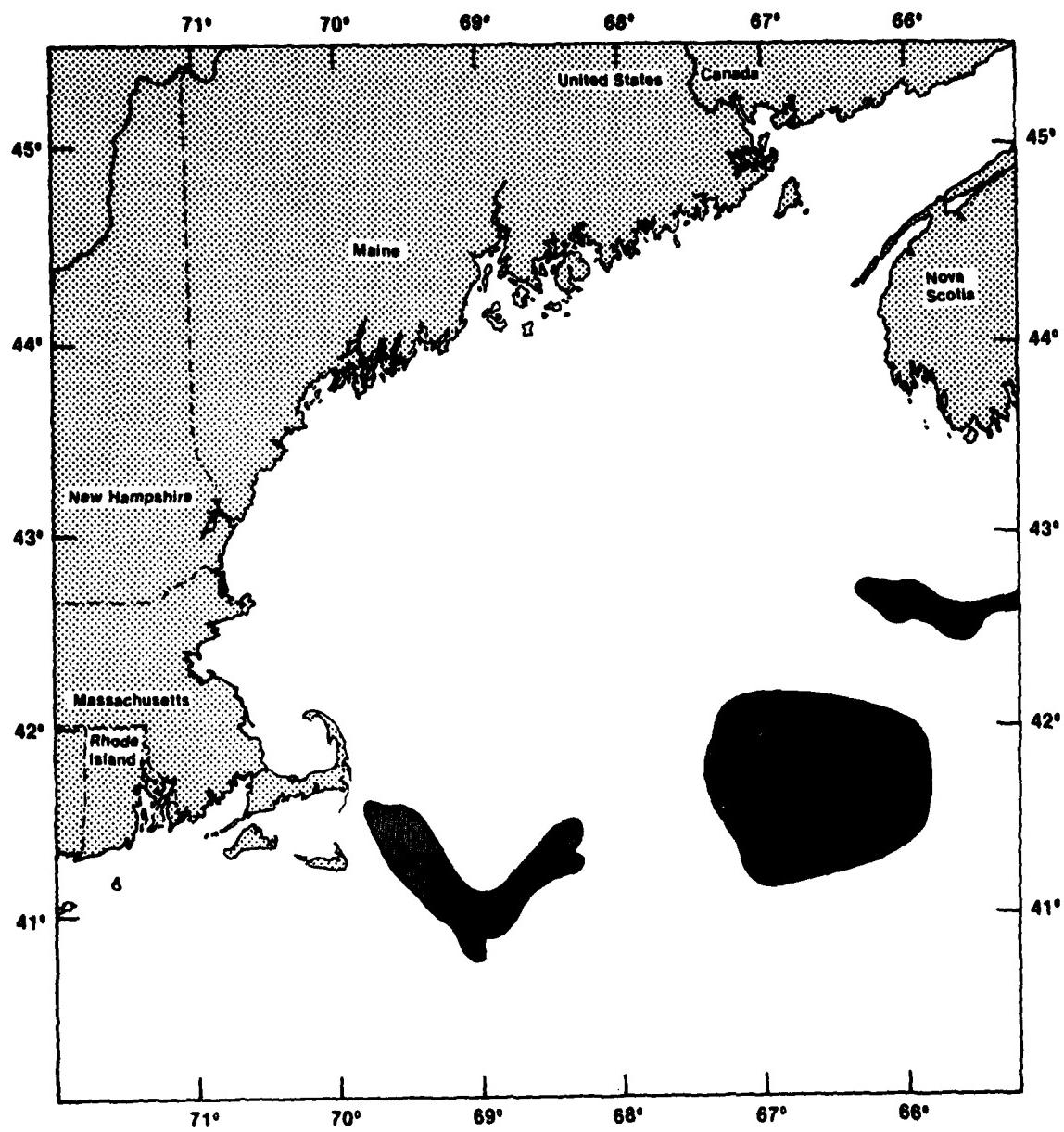


Figure 87.--Haddock Spawning Areas (April-June) (after Ray and Dobbin, 1980).

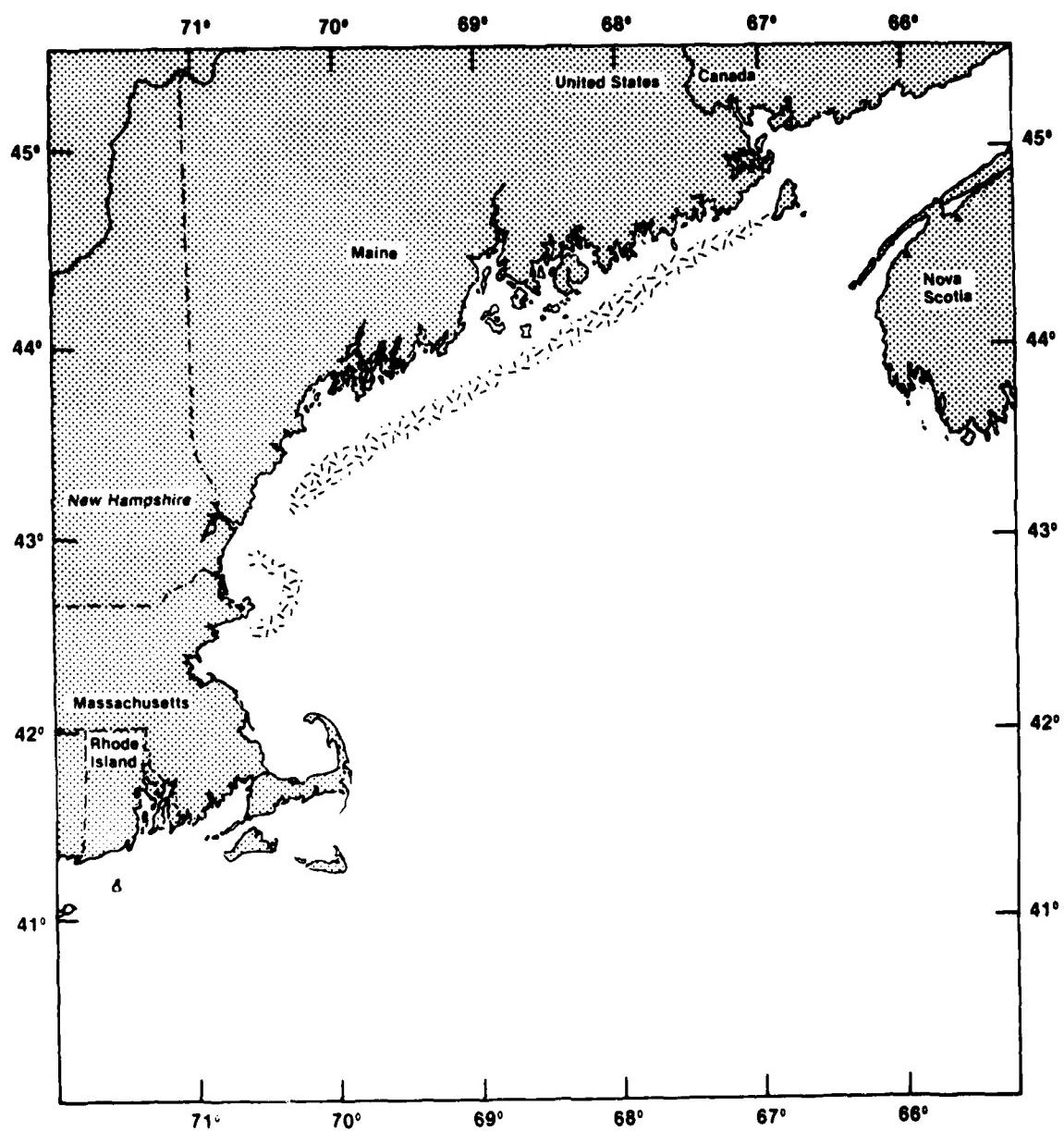


Figure 88.--Halibut Distribution (after Freeman and Walford - I, II, 1974).

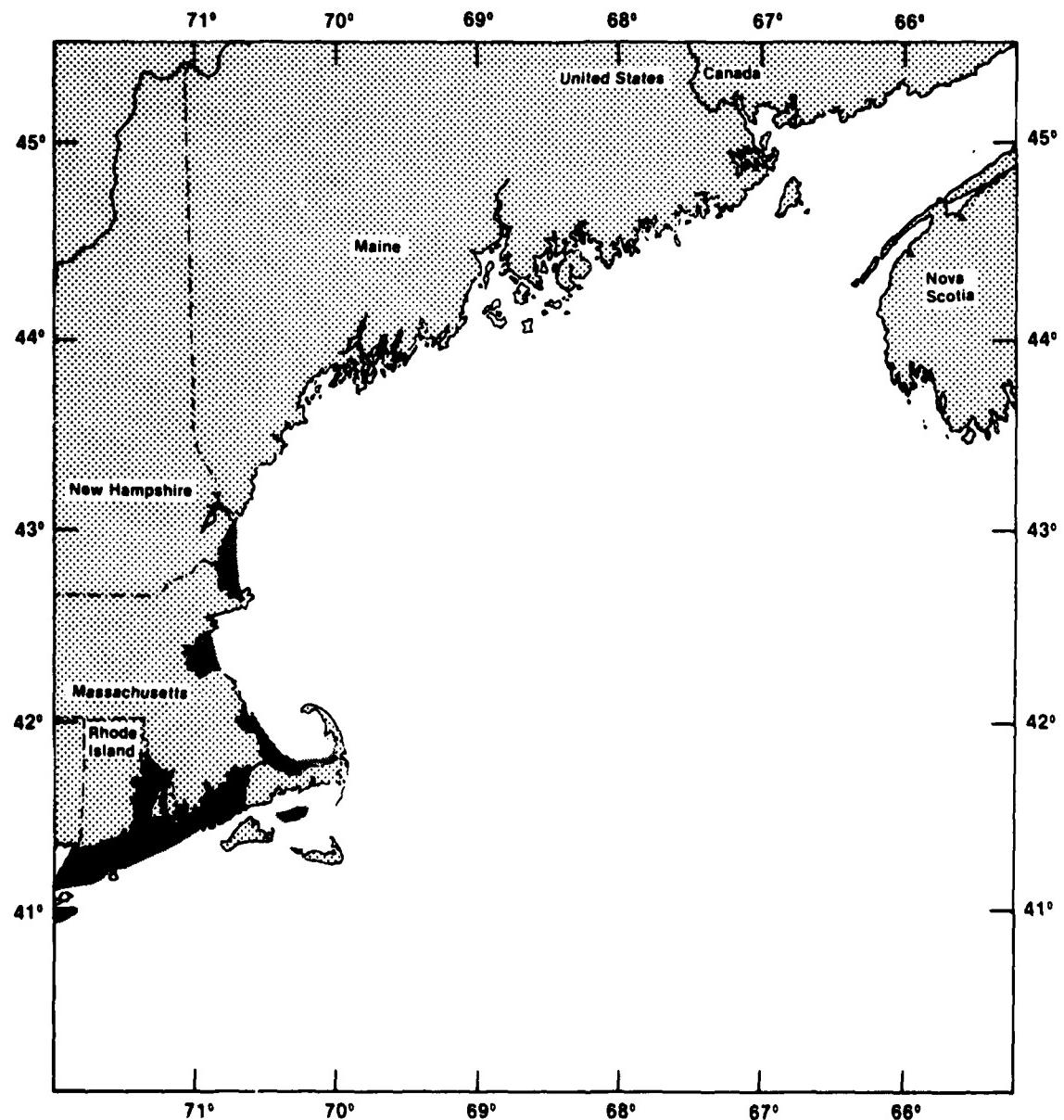


Figure 89.--Tautog Distribution (after Freeman and Walford - I, II, 1974).

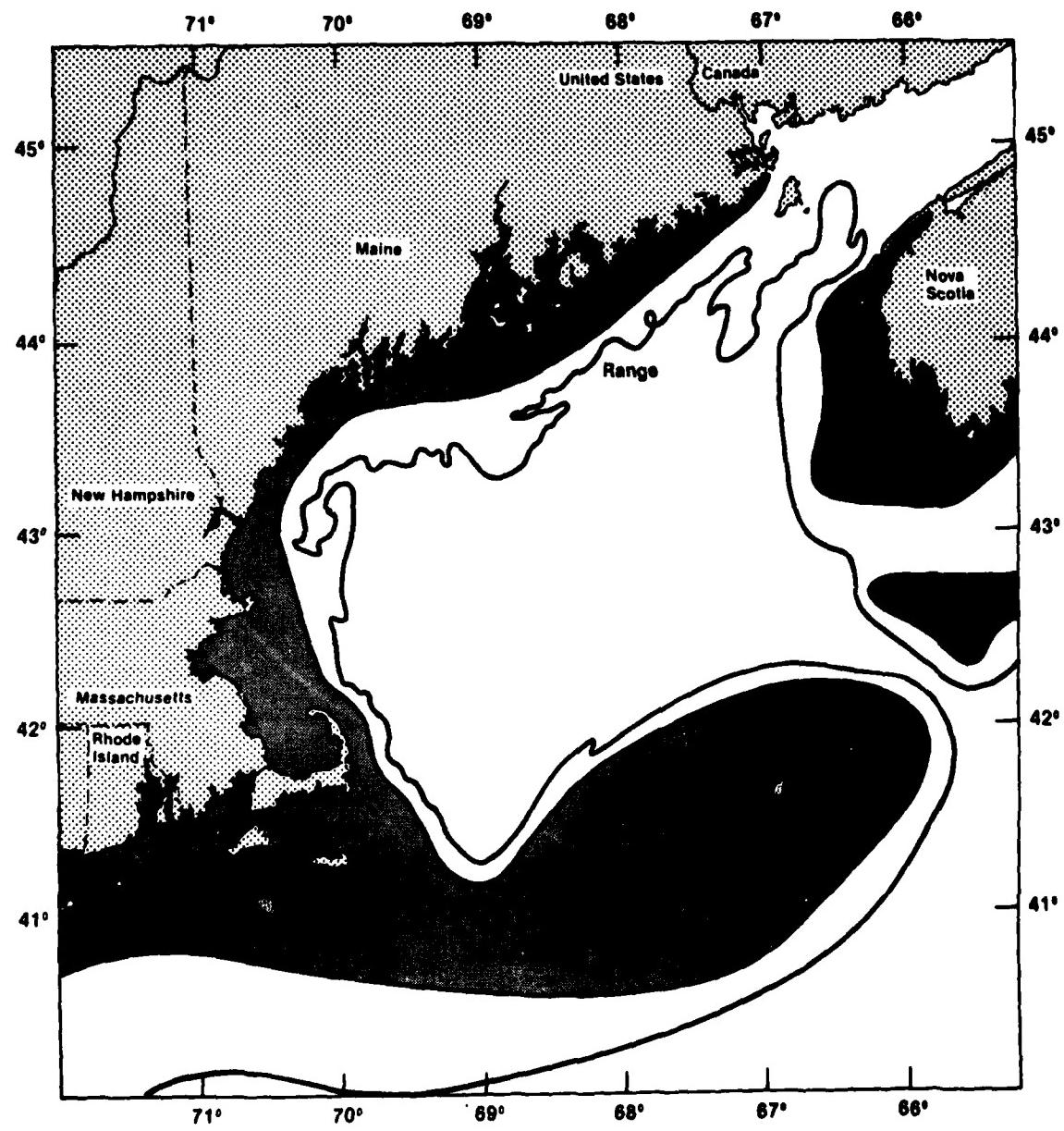


Figure 90.--Winter Flounder Distribution (after Ray and Dobbin, 1980).

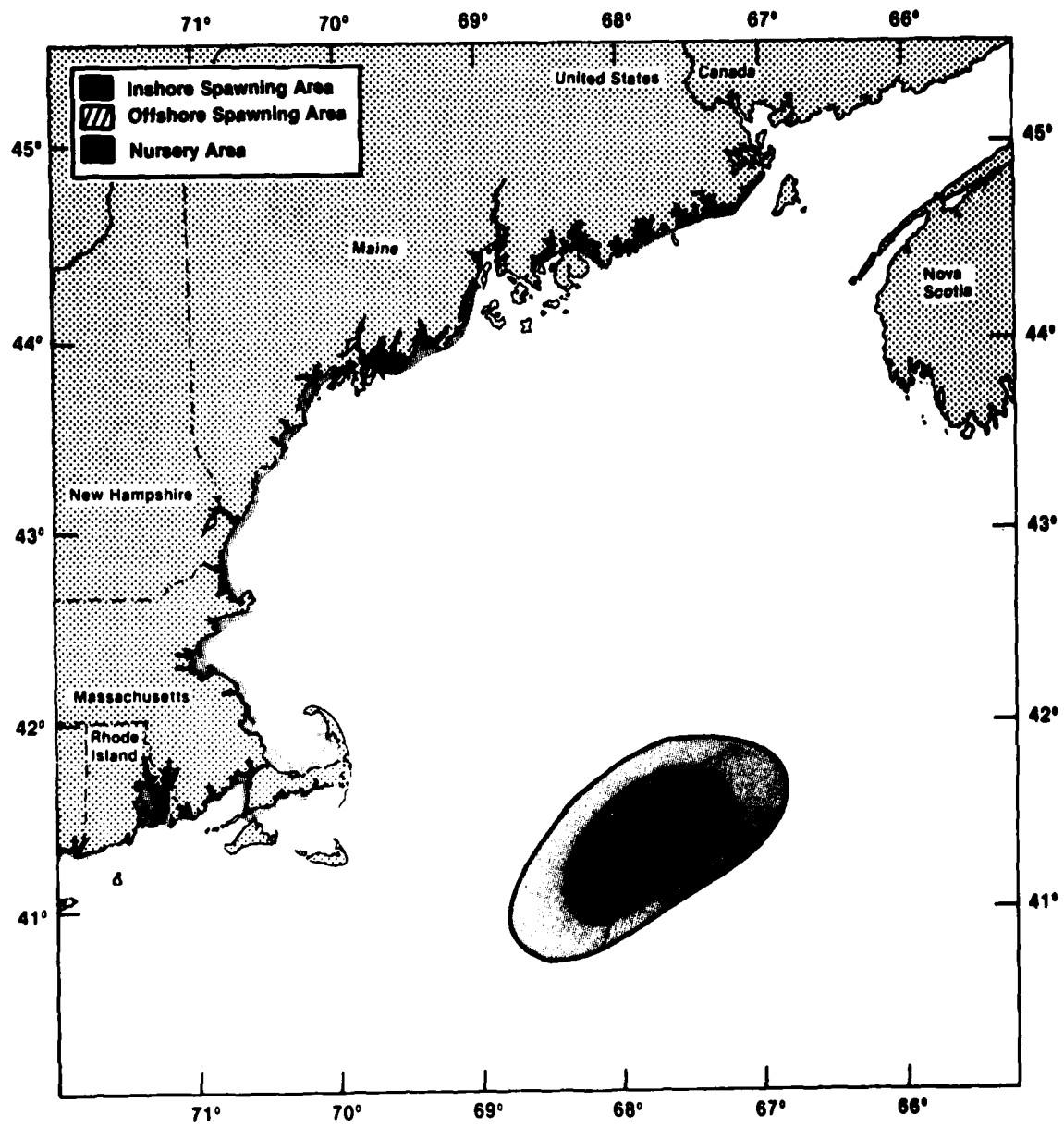


Figure 91.--Winter Flounder Spawning and Nursery Area (after Ray and Dobbin, 1980).

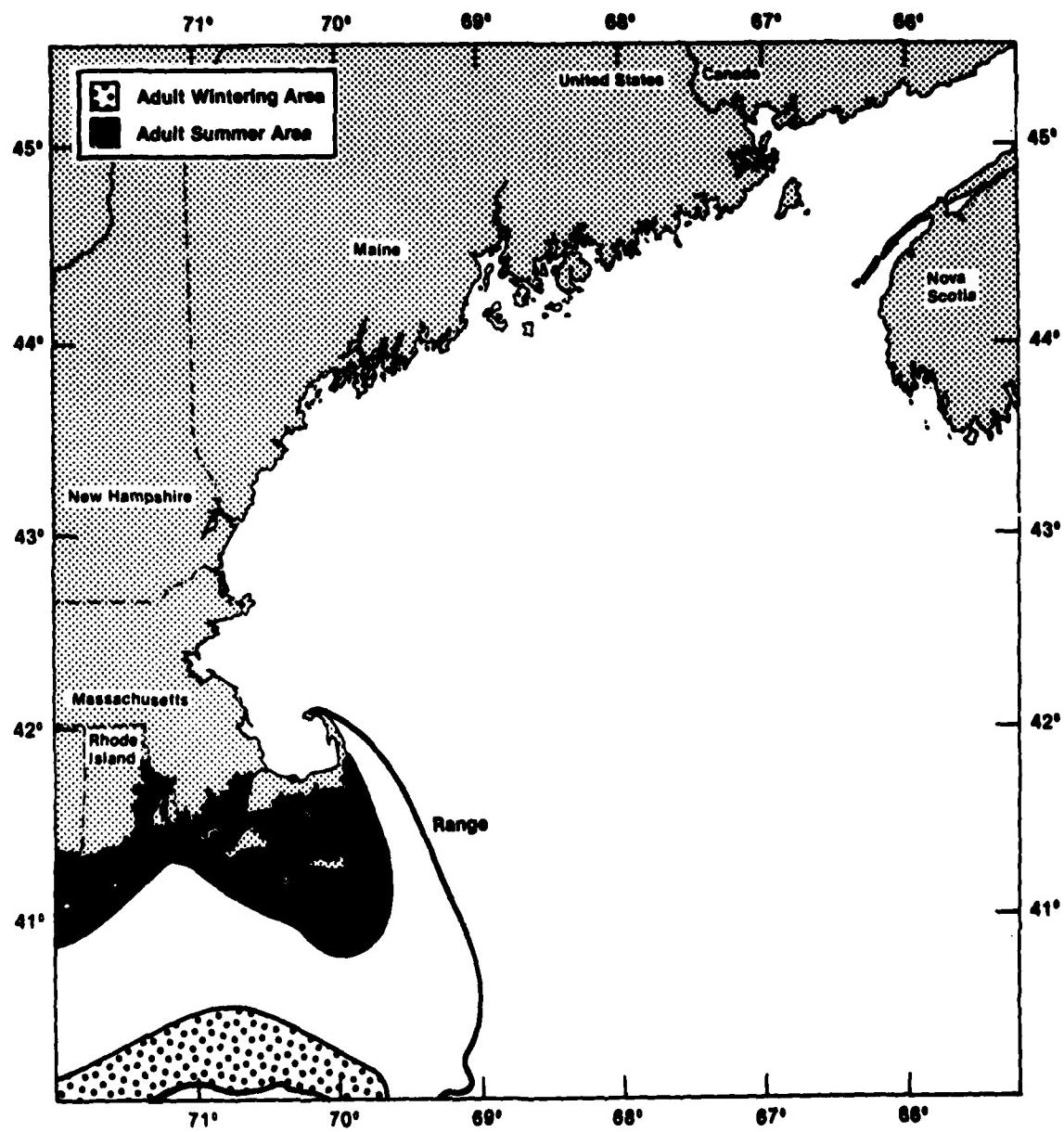


Figure 92.--Summer Flounder Distribution (after Ray and Dobbin, 1980).

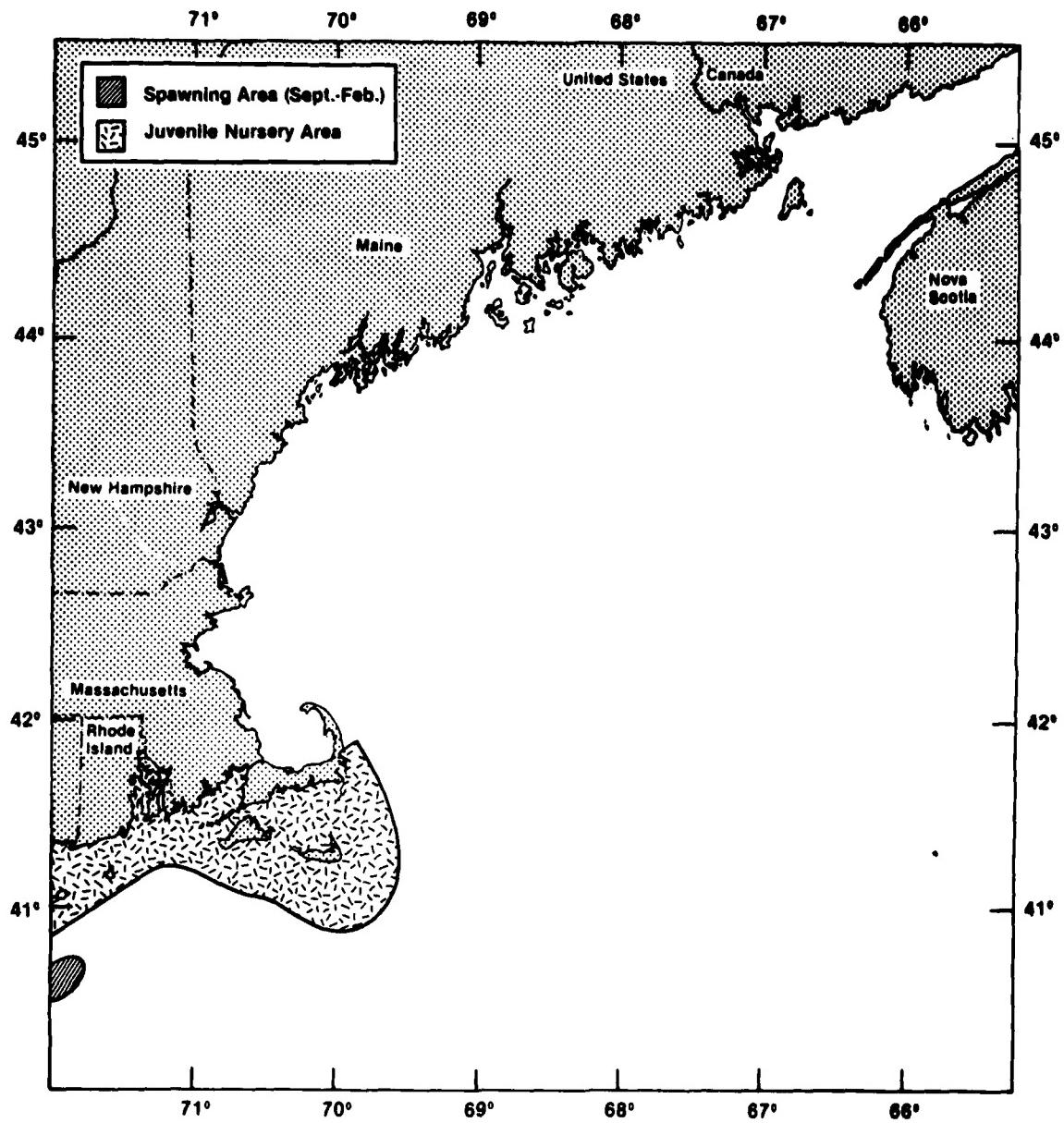


Figure 93.--Summer Flounder Spawning And Nursery Area (after Ray and Dobbin, 1980).

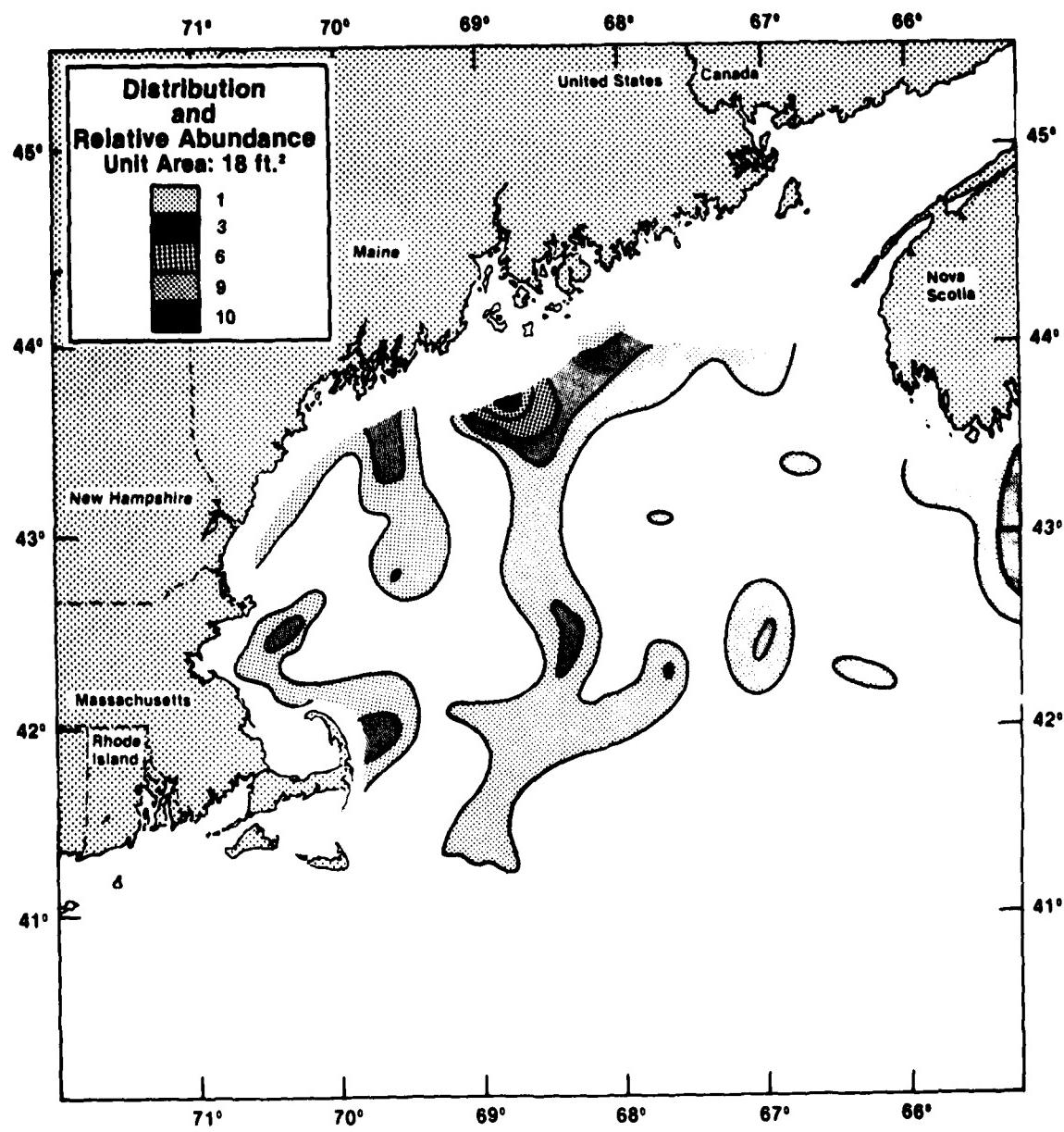


Figure 94.--Winter Flounder Distribution (after Fritz, 1965).

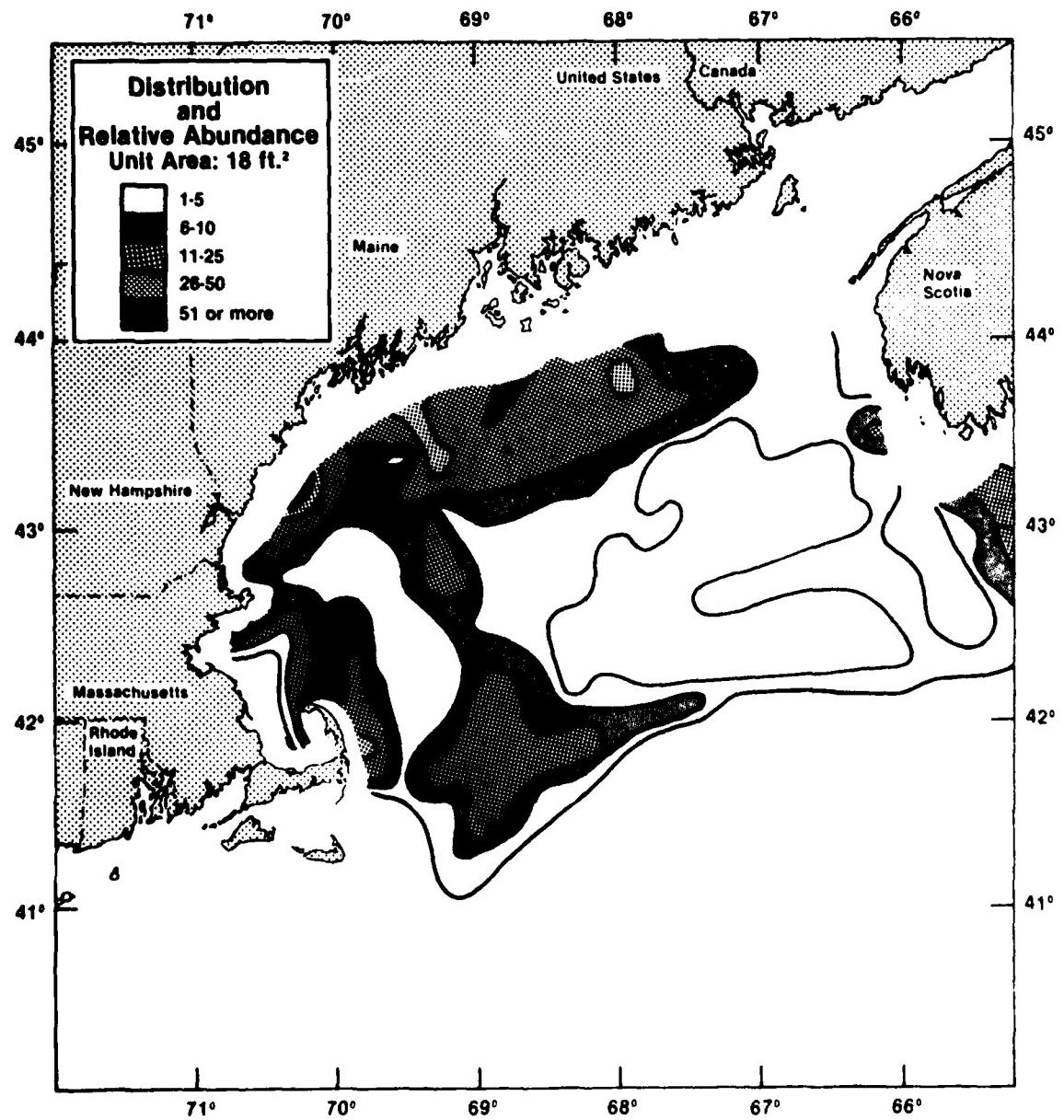


Figure 95.--American Dab (Flounder) Distribution (after Fritz, 1965).

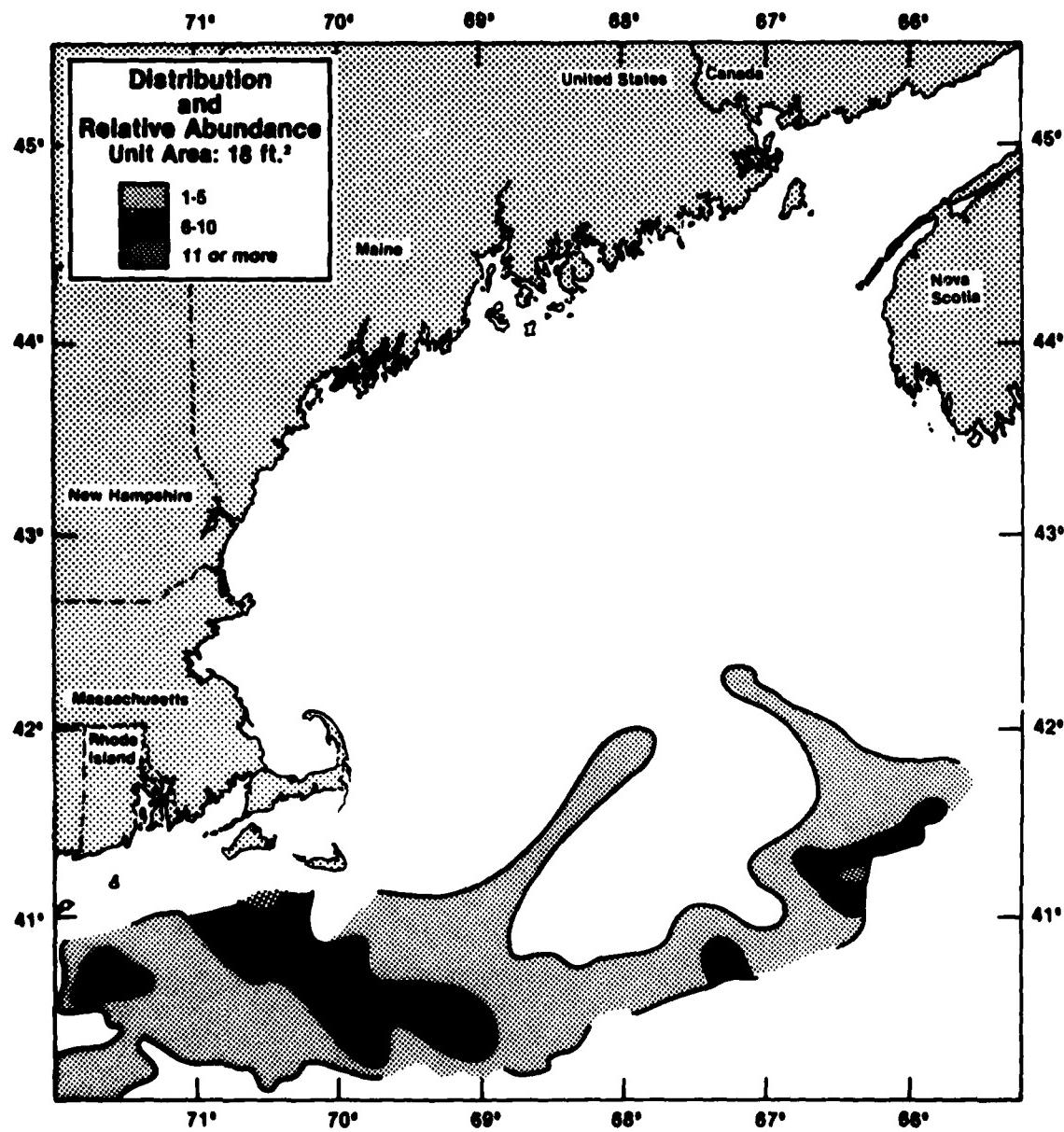


Figure 96.--Four Spot Flounder Distribution (after Fritz, 1965).

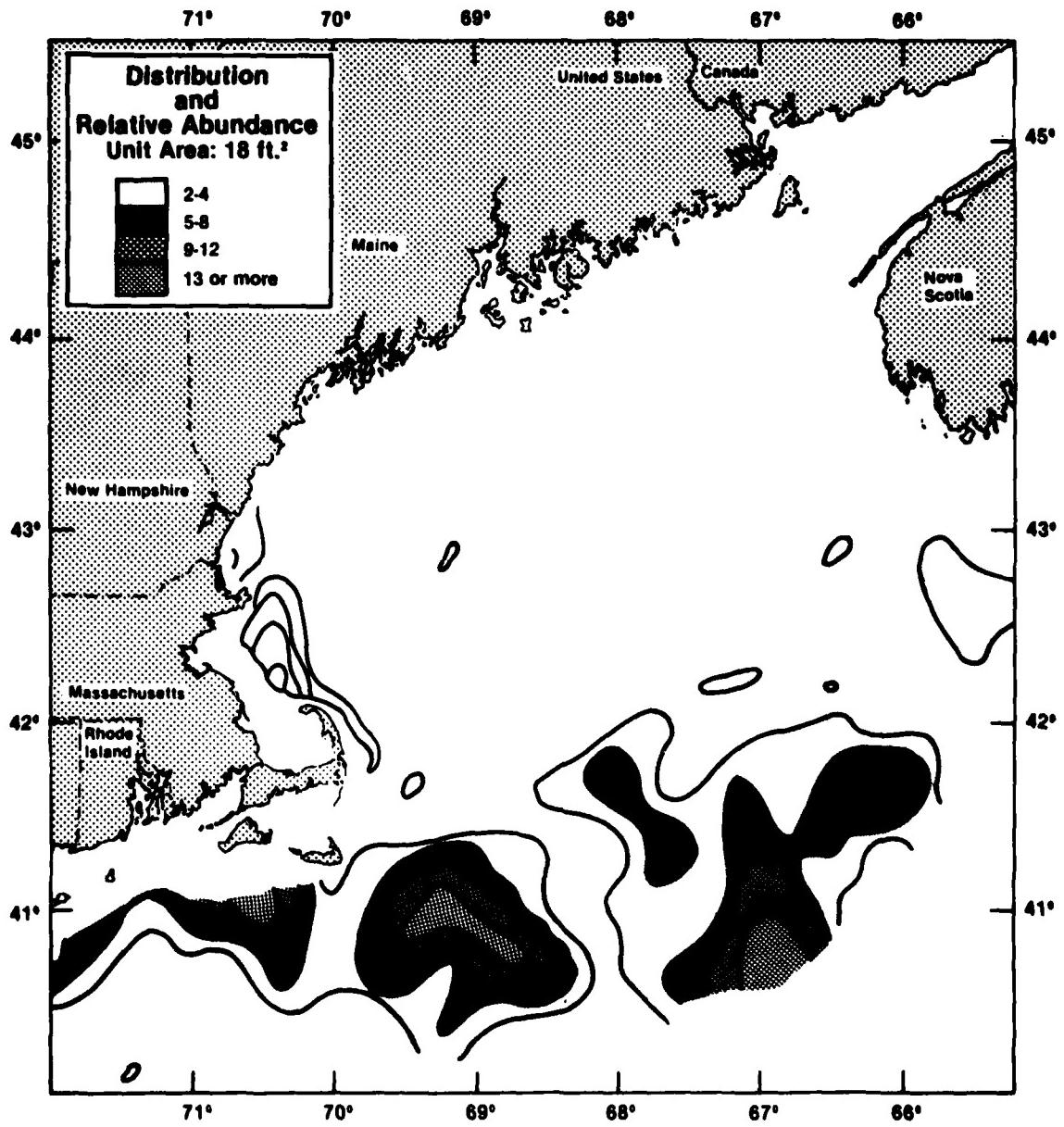


Figure 97.--Yellowtail Flounder Distribution (after Fritz, 1965).

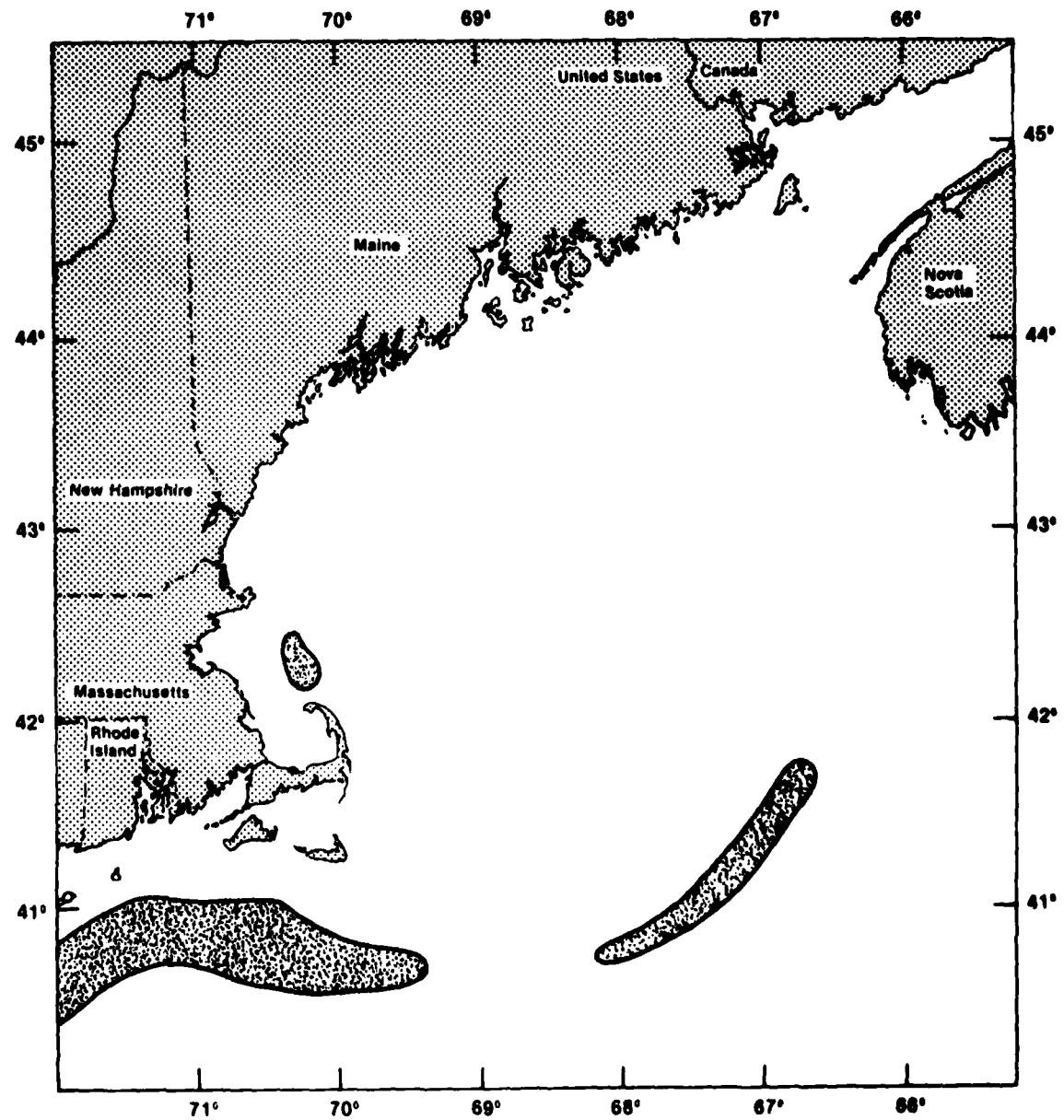


Figure 98.--Yellowtail Flounder Spawning Areas (April-May) (after Ray and Dobbin, 1980).

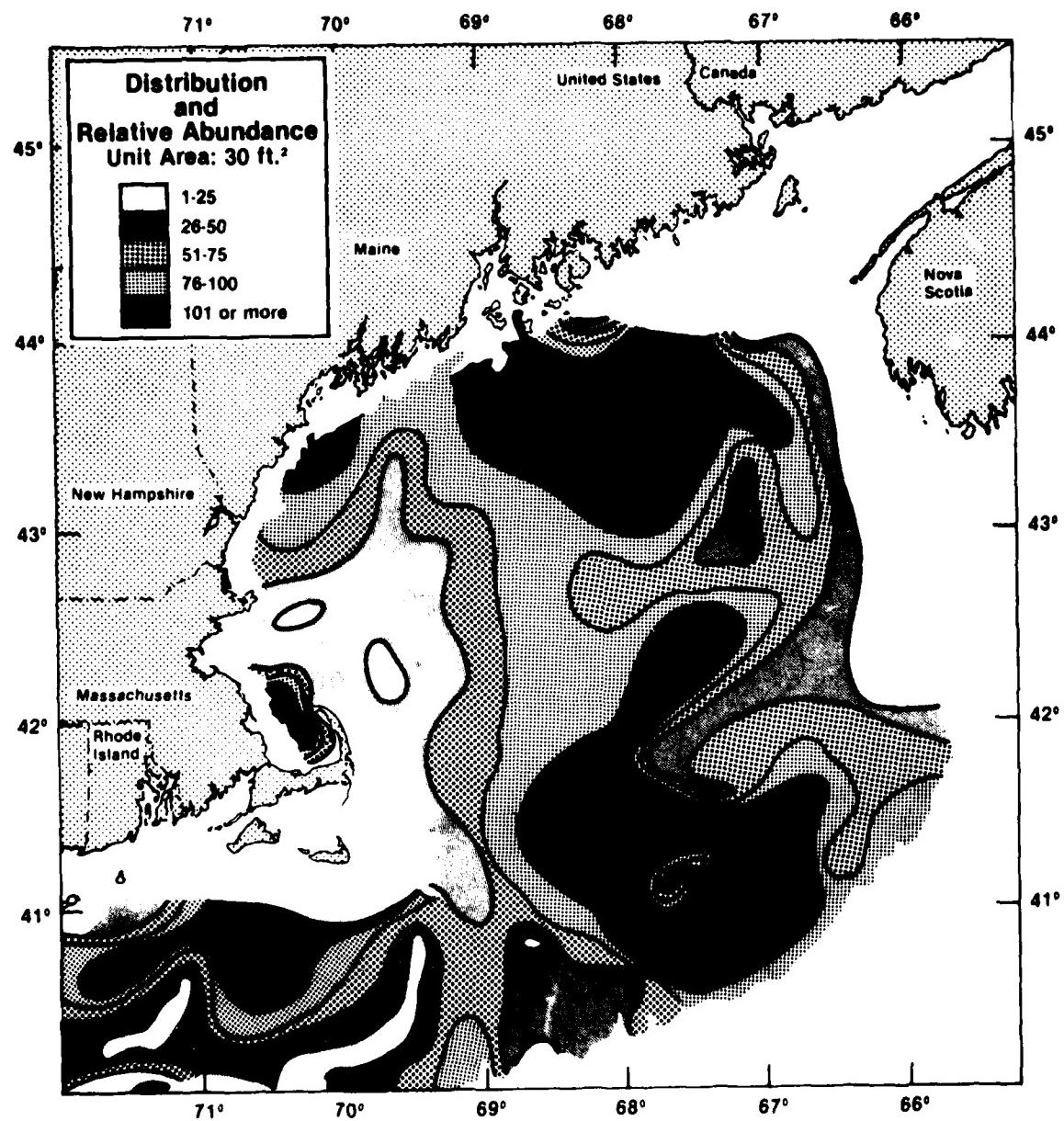


Figure 99.--Silver Hake Distribution (after Fritz, 1965).

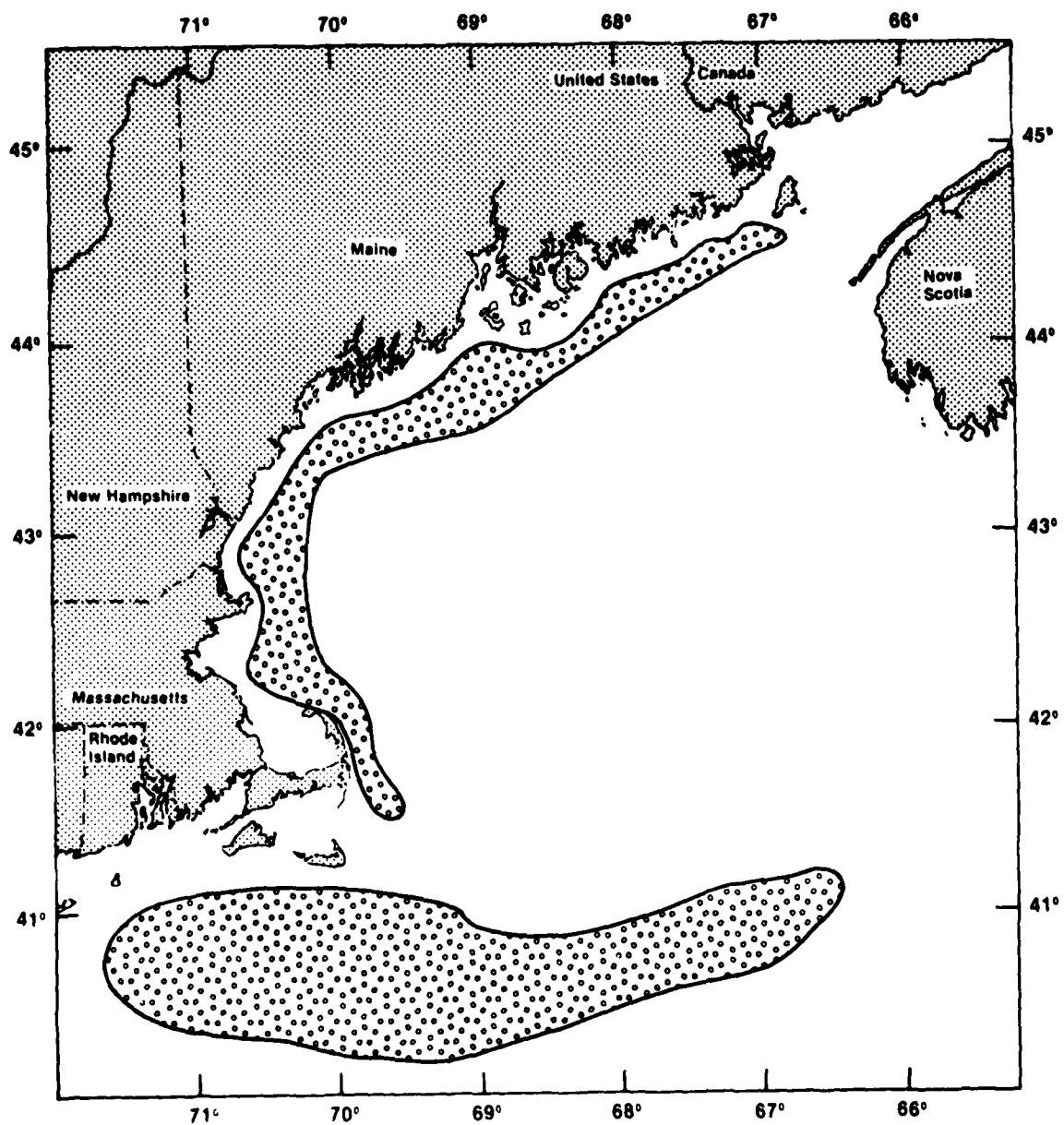


Figure 100.--Silver Hake Spawning Areas (June-August) (after Ray and Dobbins, 1980).

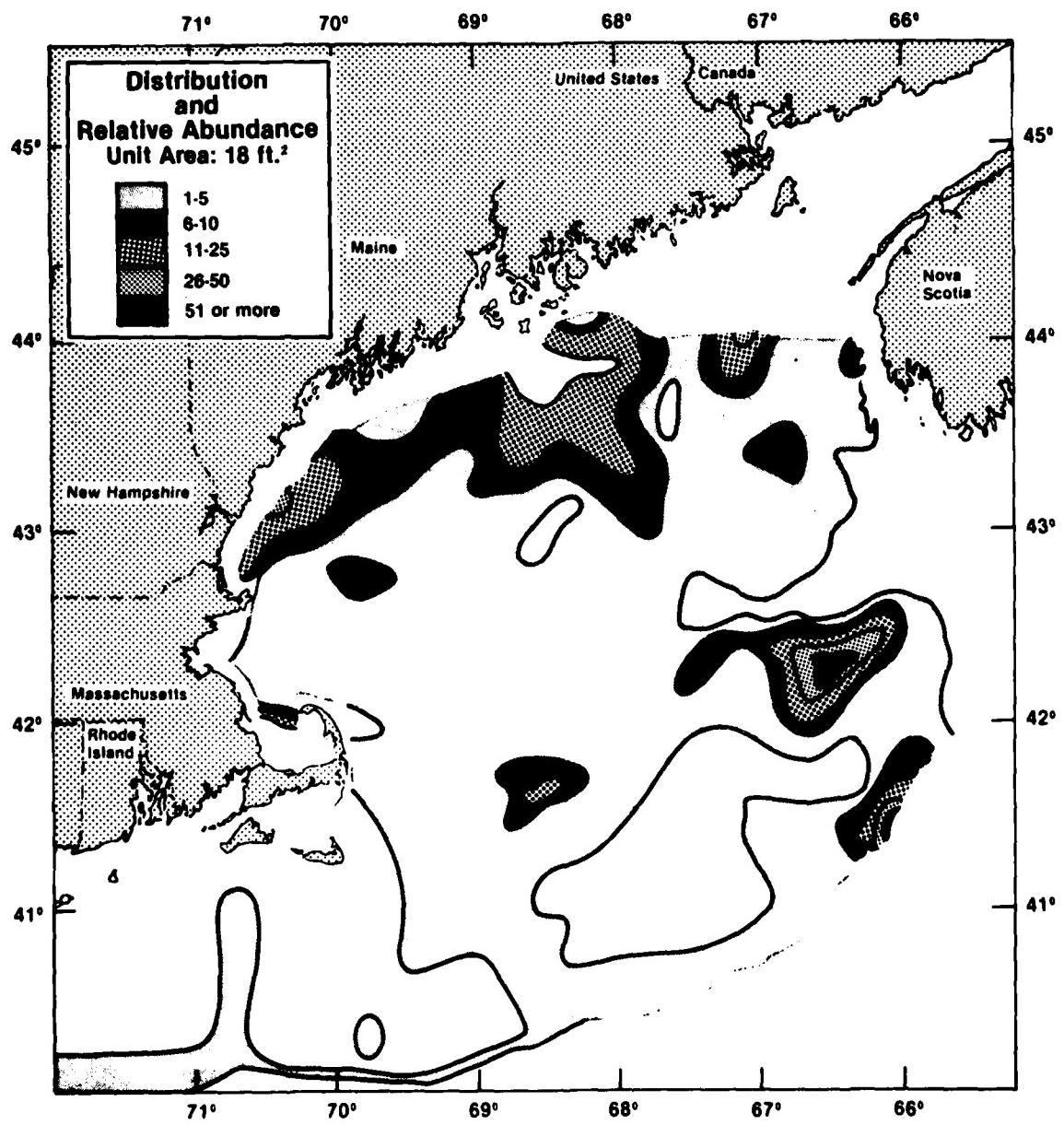


Figure 101.--White Hake Distribution (after Fritz, 1965).

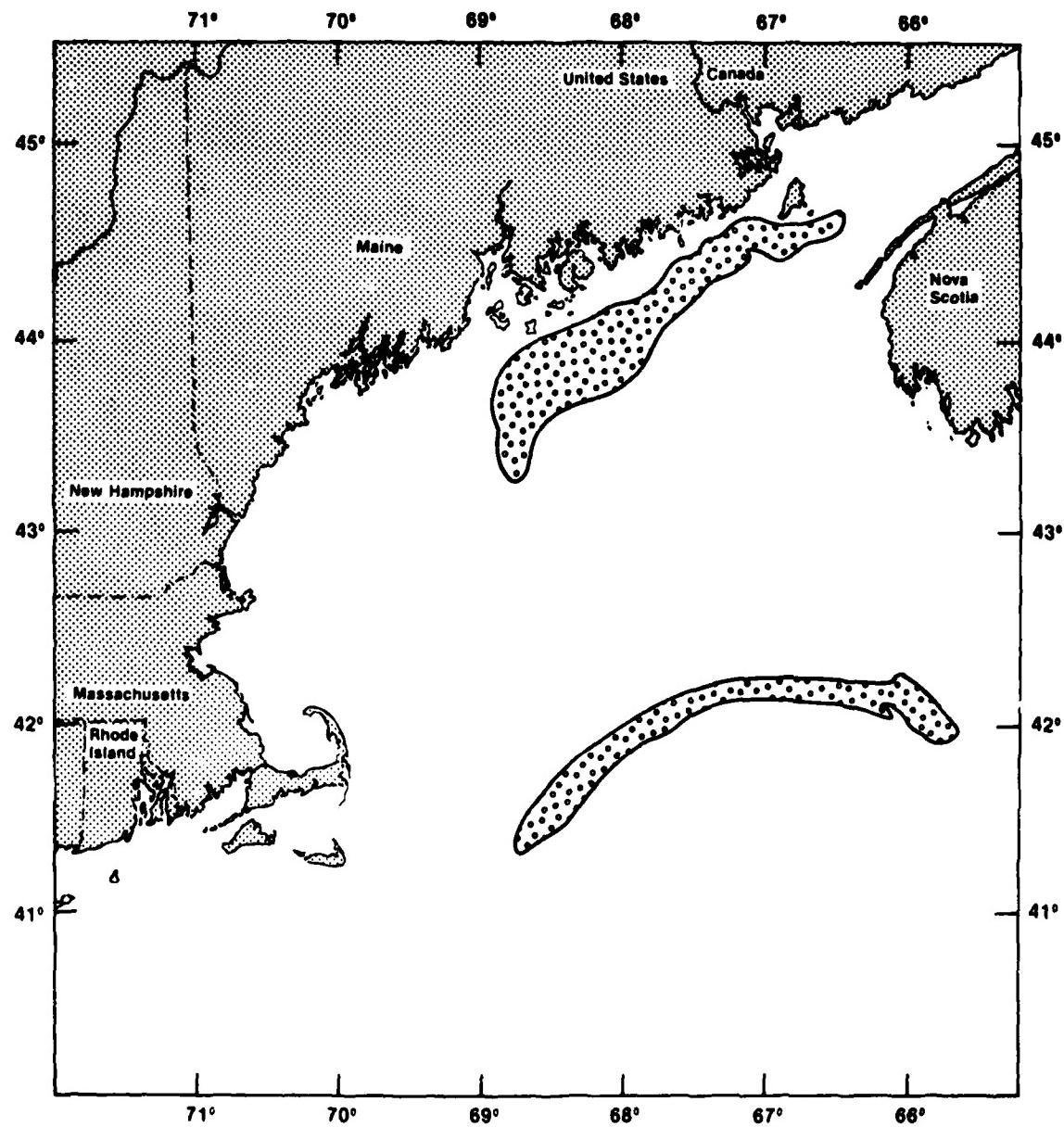


Figure 102.--White Hake Spawning Areas (after Ray and Dobbin, 1980).

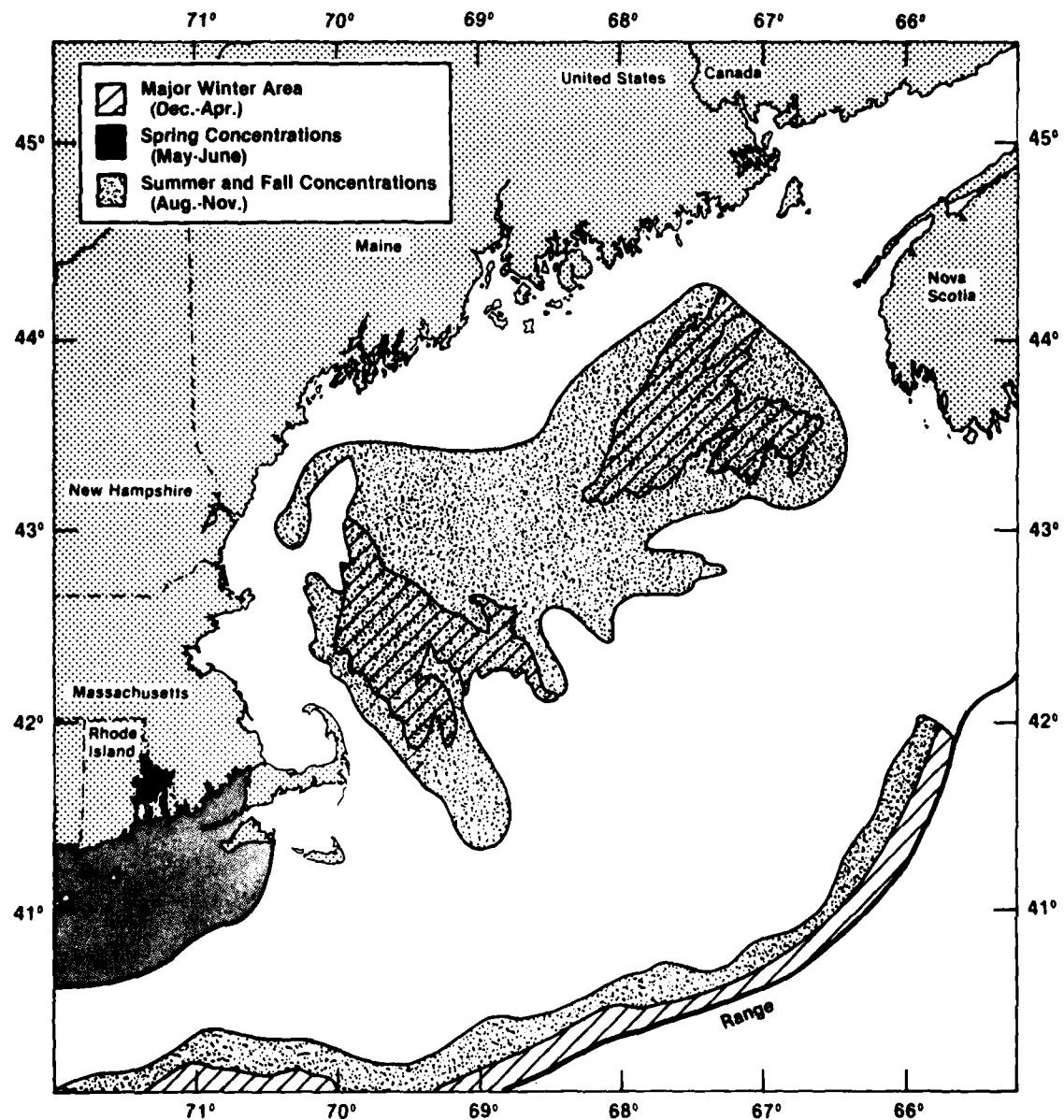


Figure 103.--Red Hake Distribution (after Ray and Dobbin, 1980).

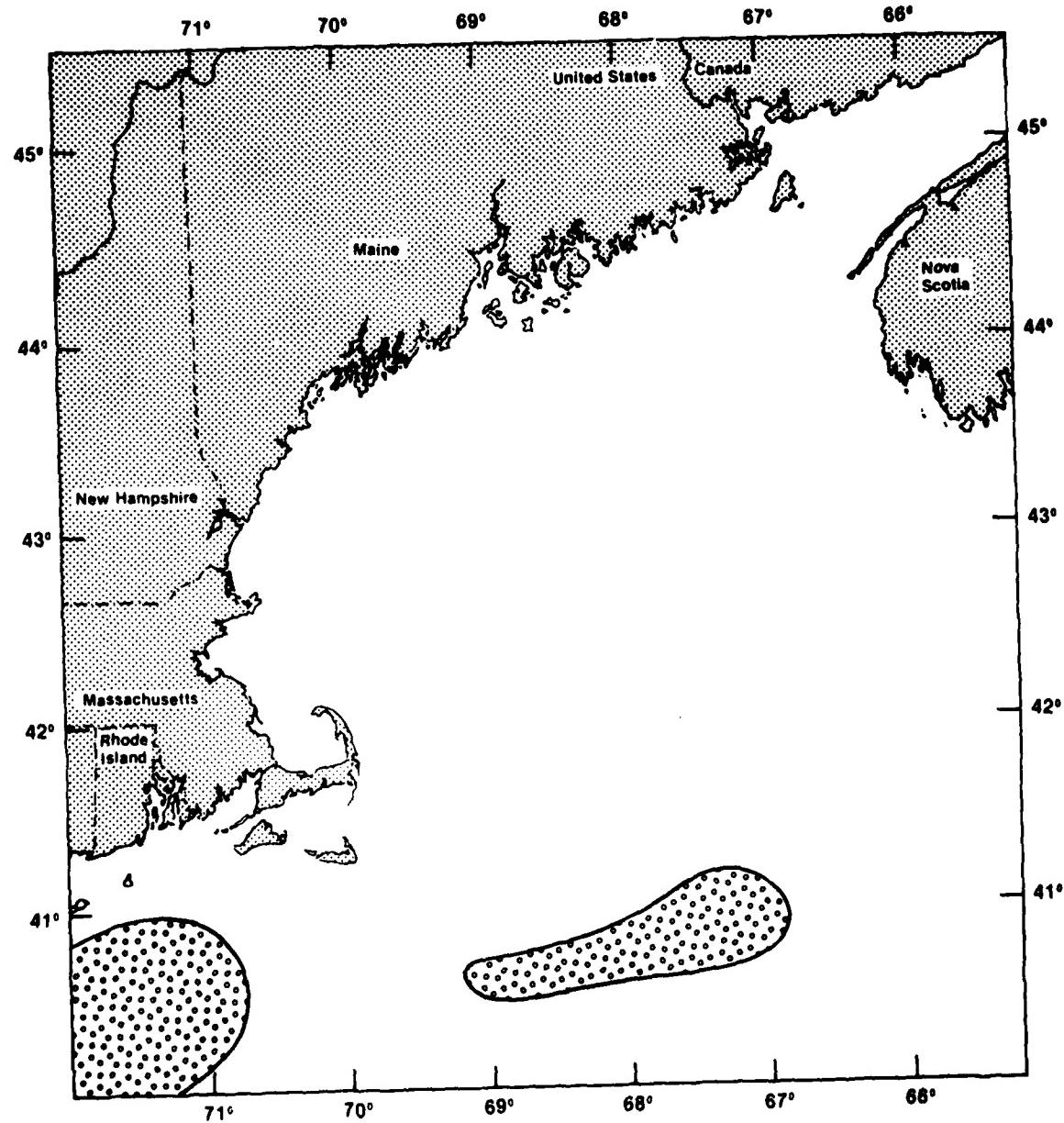


Figure 104.--Red Hake Spawning Areas (July-August) (after Ray and Dobbin, 1980).

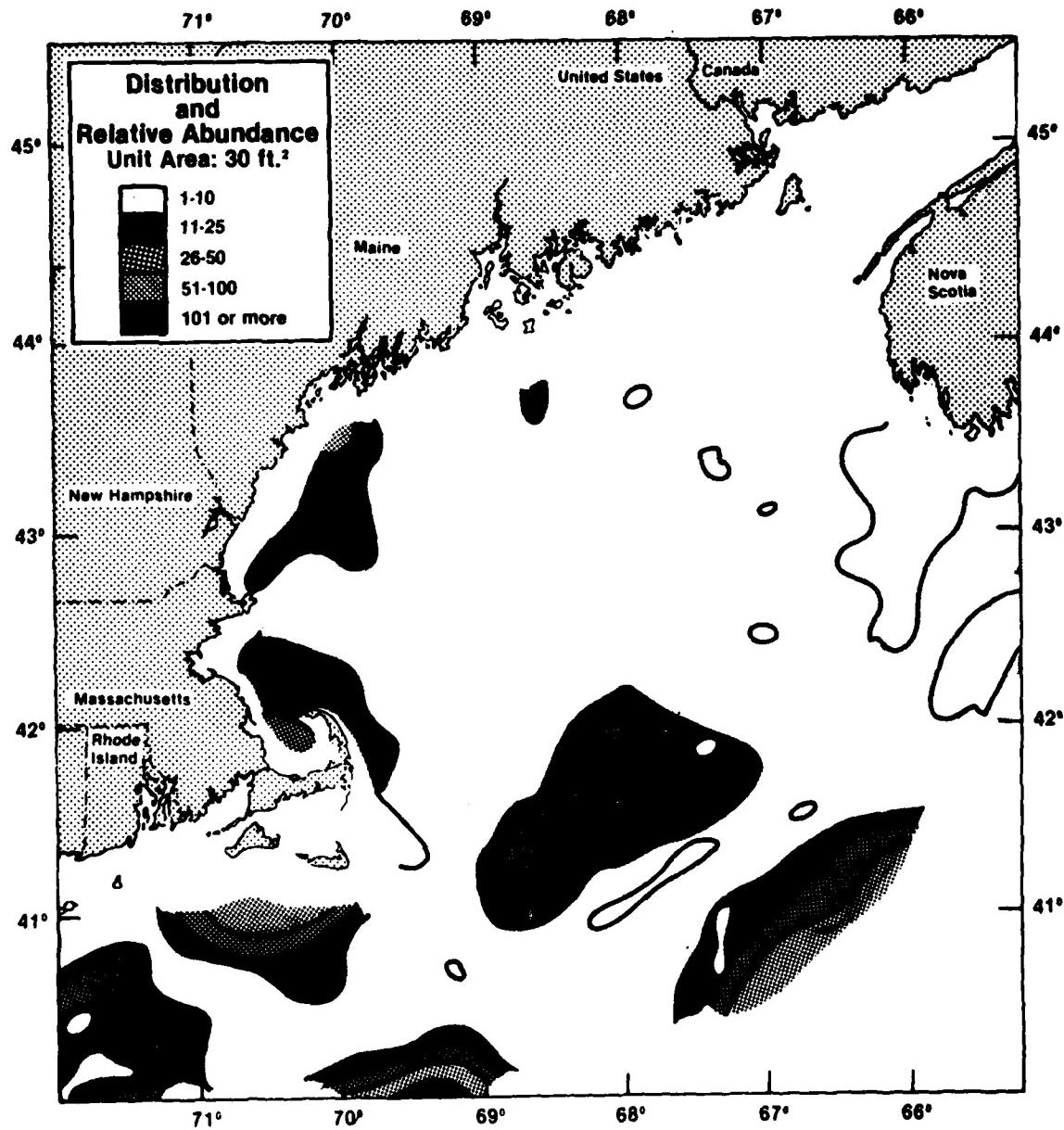


Figure 105.--Squirrel Hake Distribution (after Fritz, 1965).

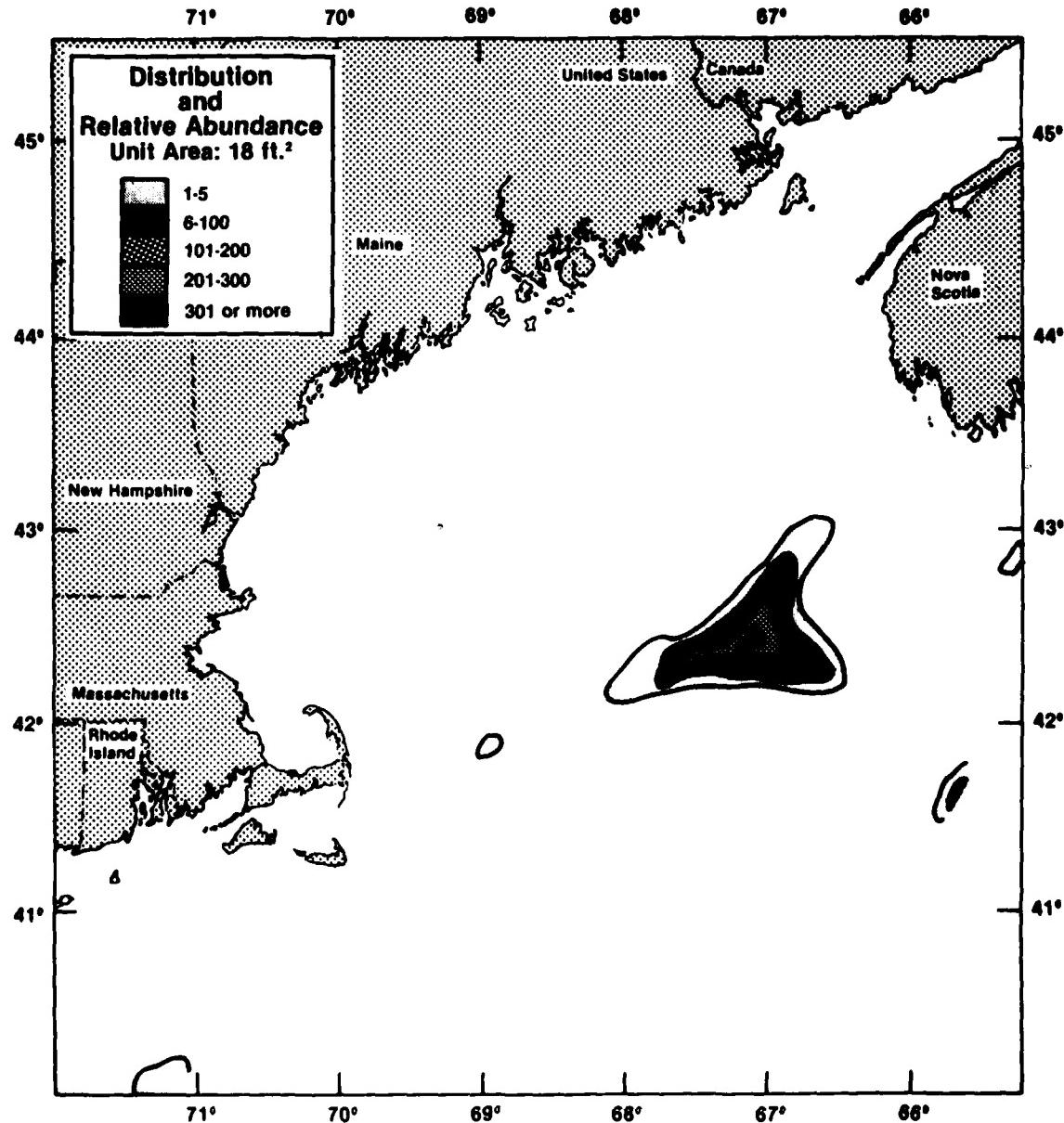


Figure 106.--Longfin Hake Distribution (after Fritz, 1965).

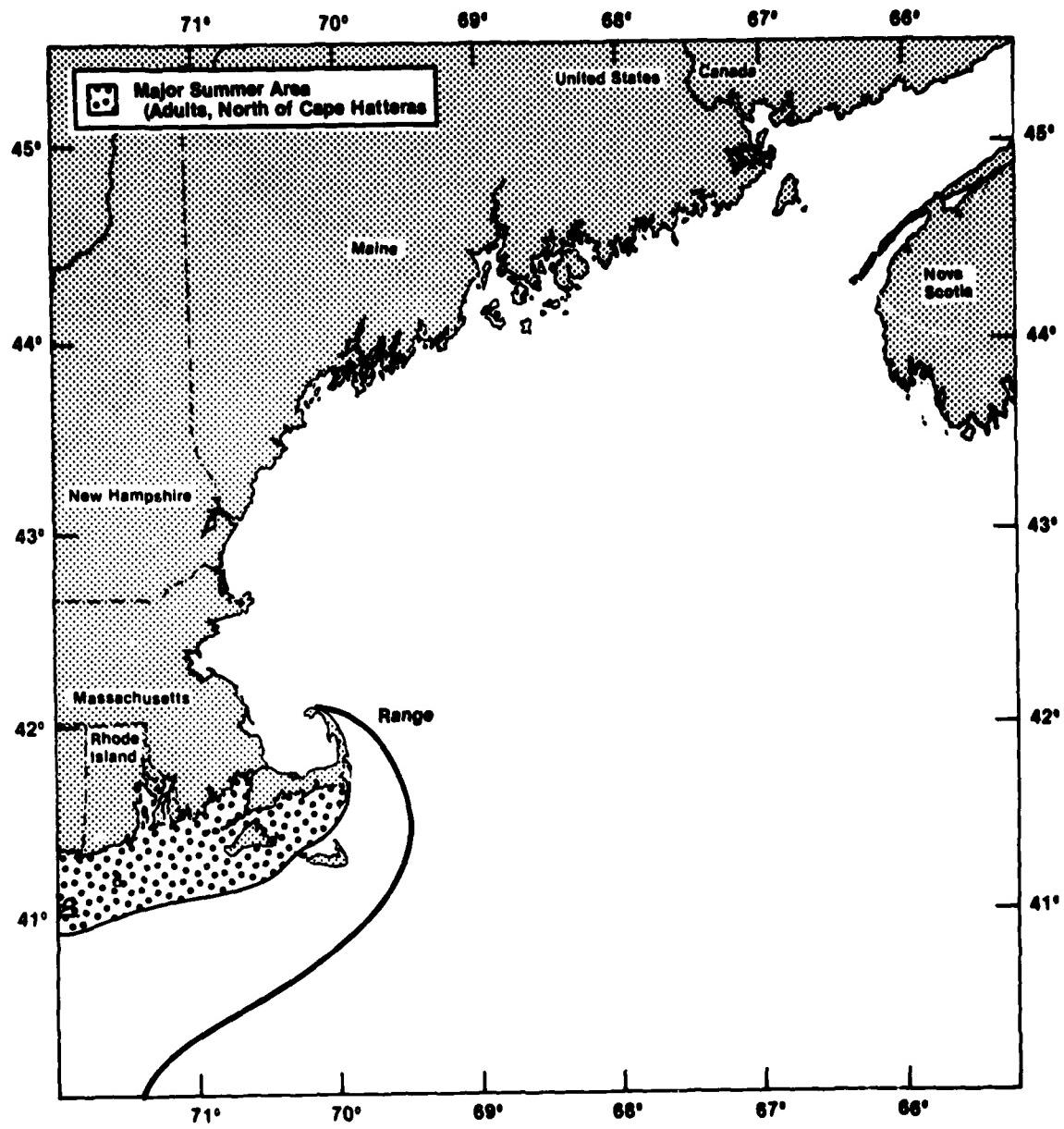


Figure 107.--Black Sea Bass Distribution (after Ray and Dobbin, 1980).

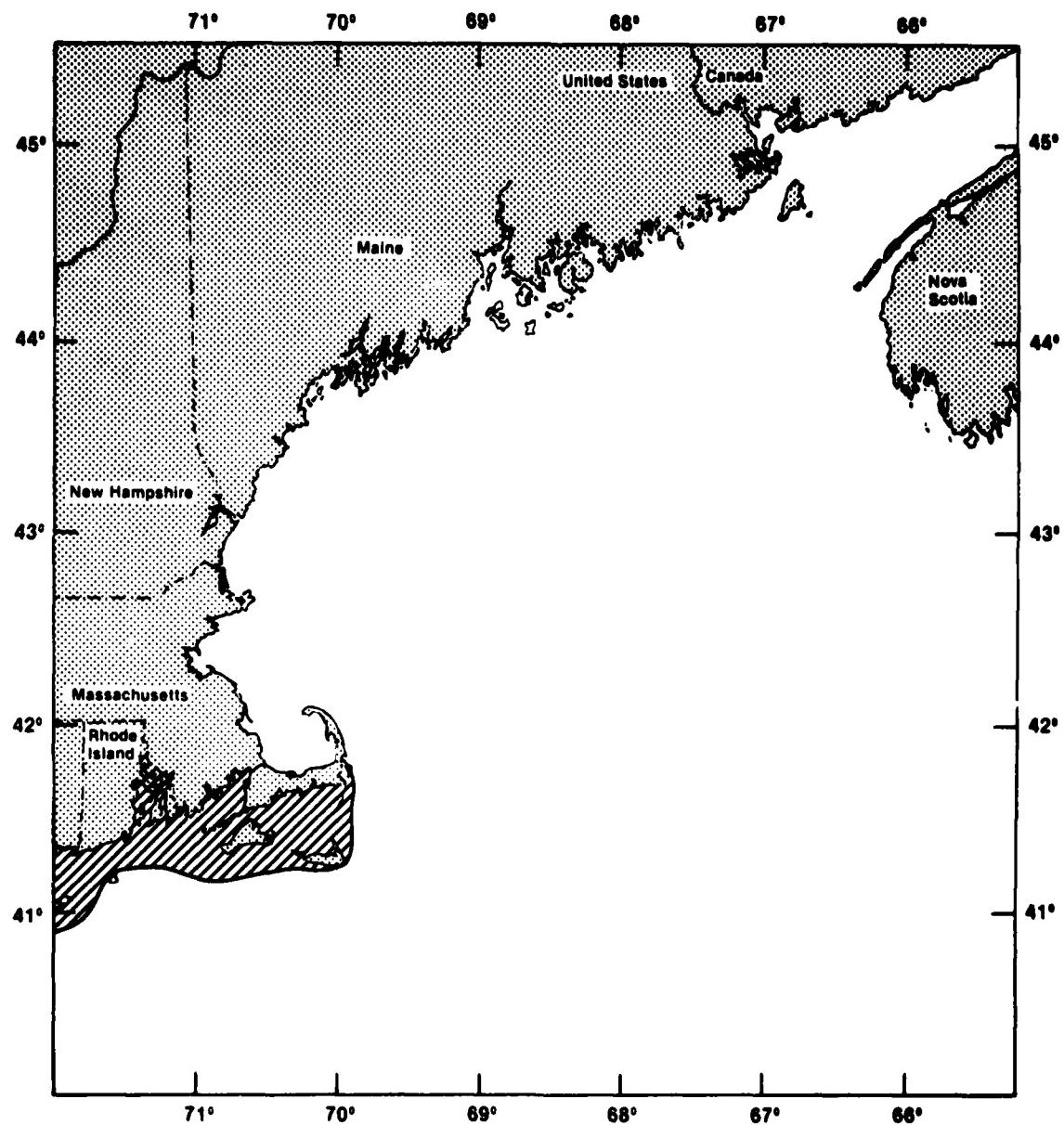


Figure 108.--Black Sea Bass Spawning (June-August) and Nursery Area (after Ray and Dobbin, 1980).

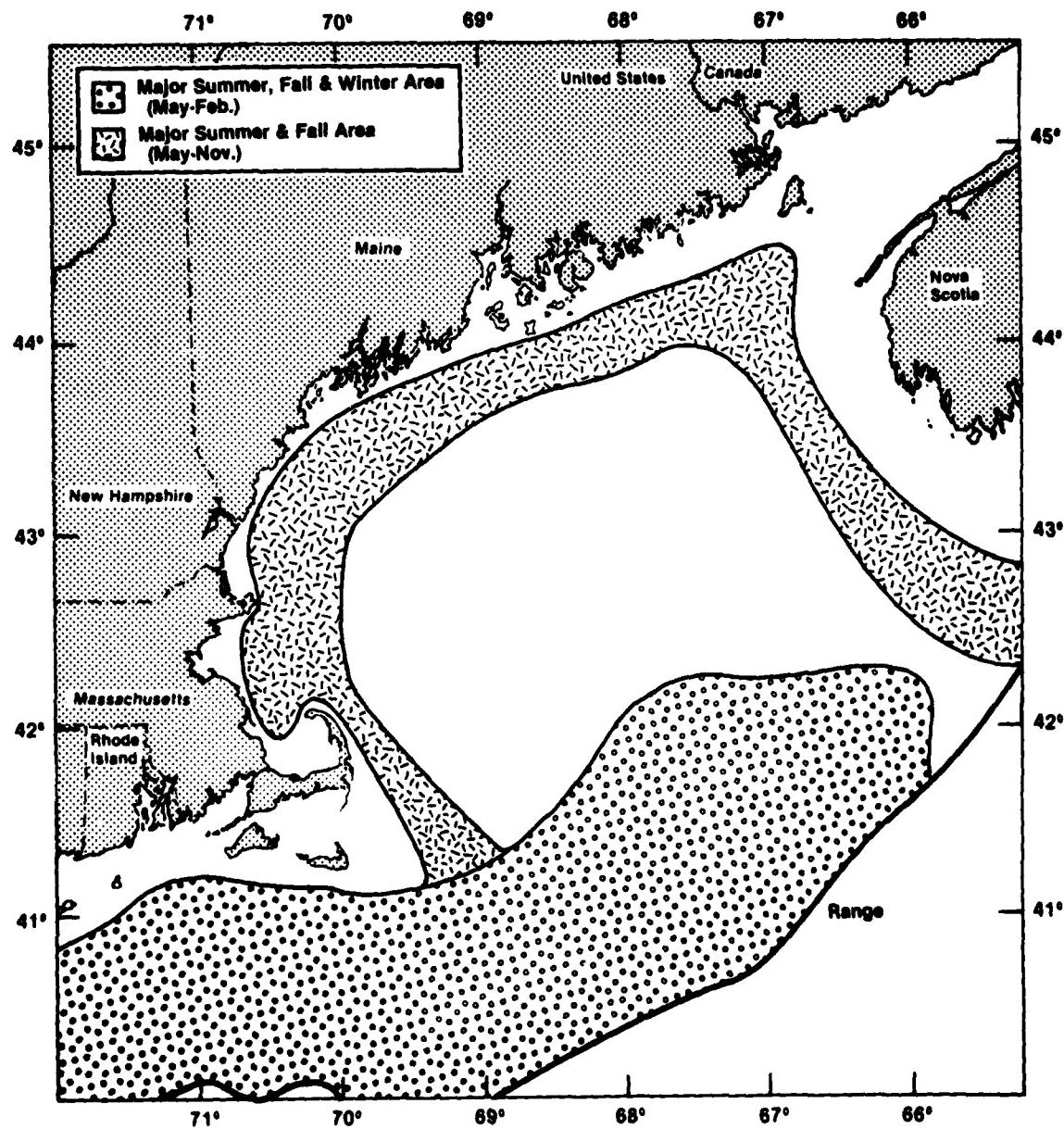


Figure 109.--American Shad Distribution (after Ray and Dobbin, 1980).

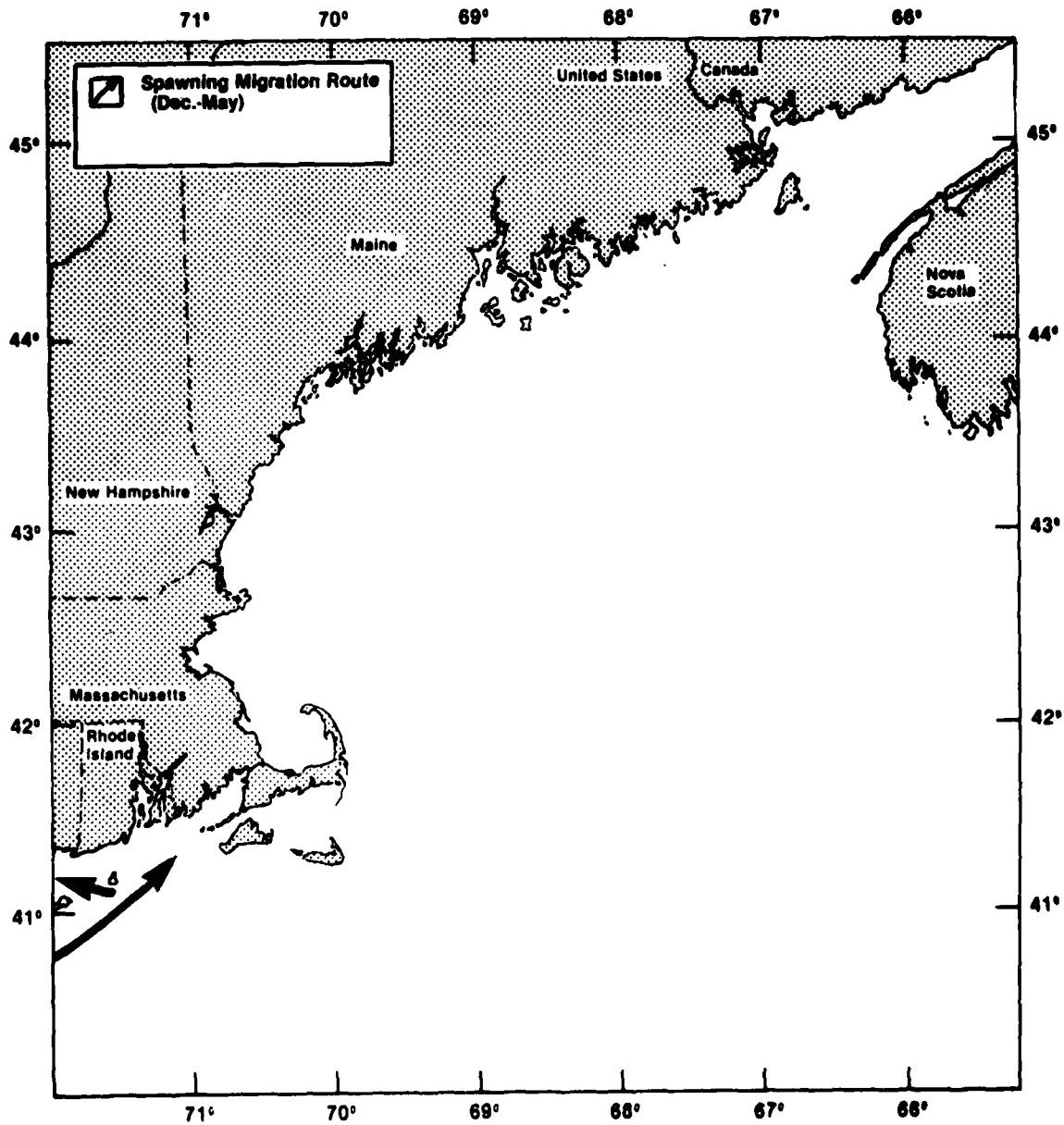


Figure 110.--American Shad Spawning Area (after Ray and Dobbin, 1980).

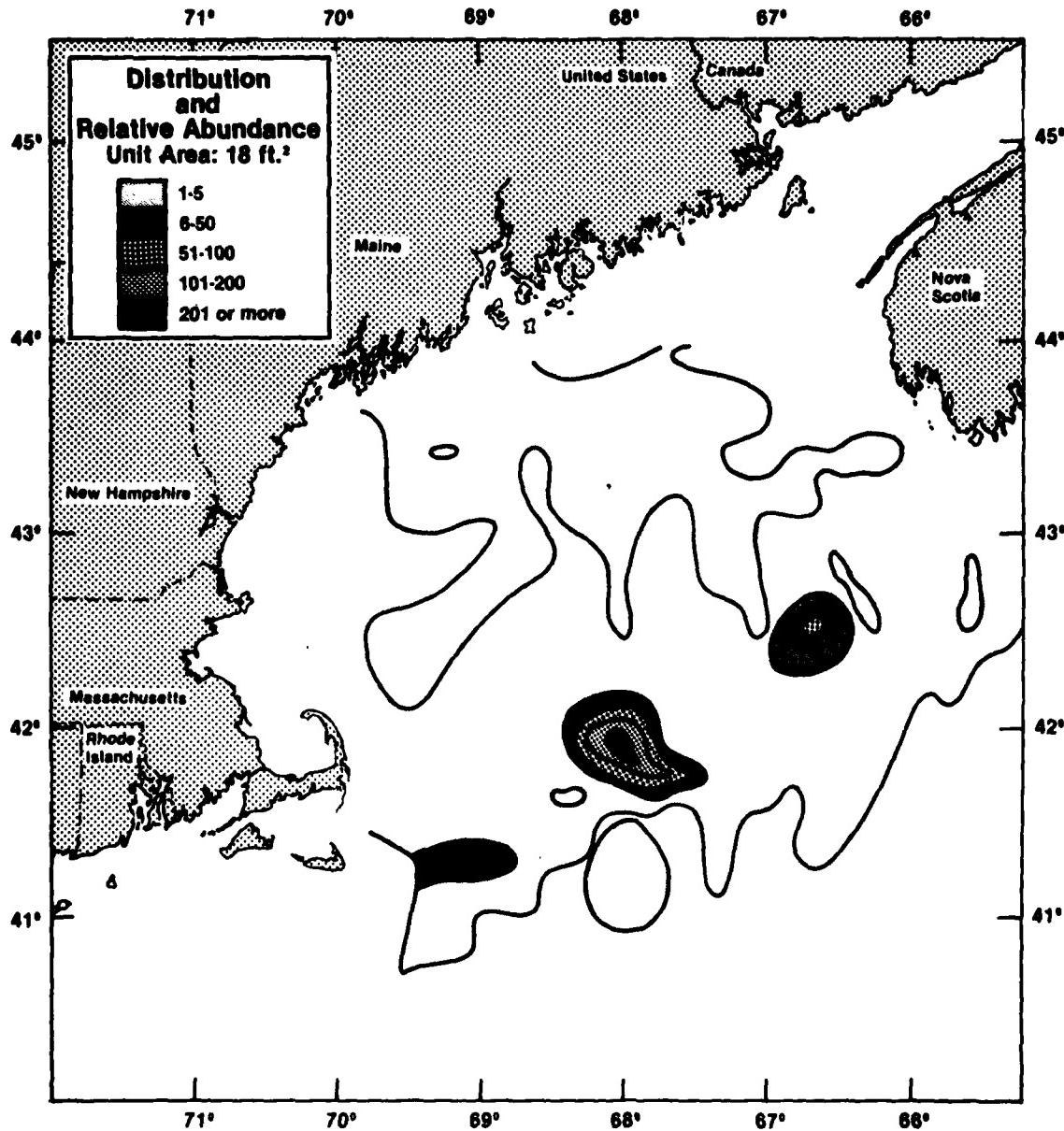


Figure 111.--Sea Herring Distribution (Dec.-May) (after Fritz, 1965).

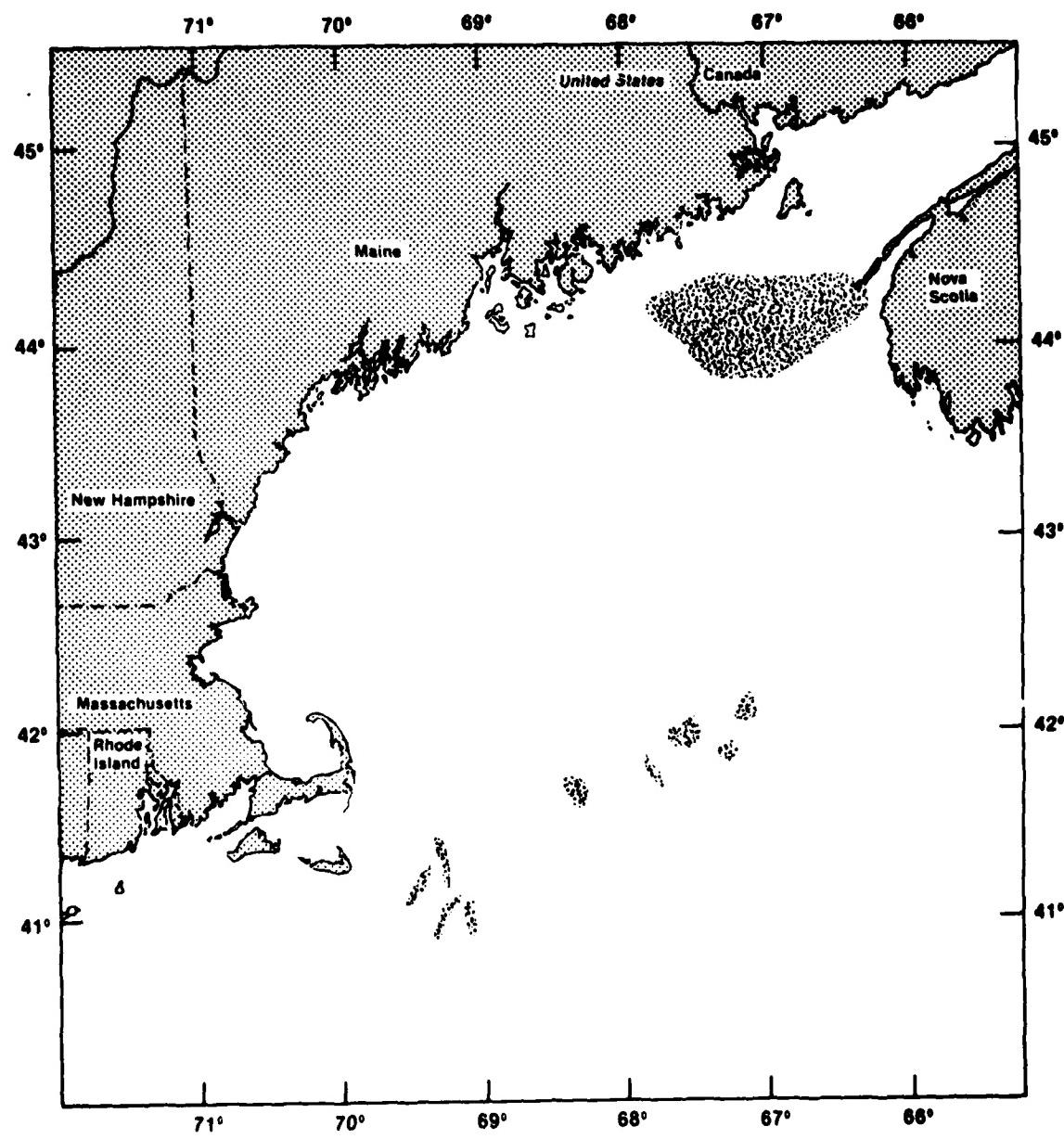


Figure 112.--Sea Herring Spawning Area (Sept.-Oct.) (after Shack, Smith & Davis, 1976).

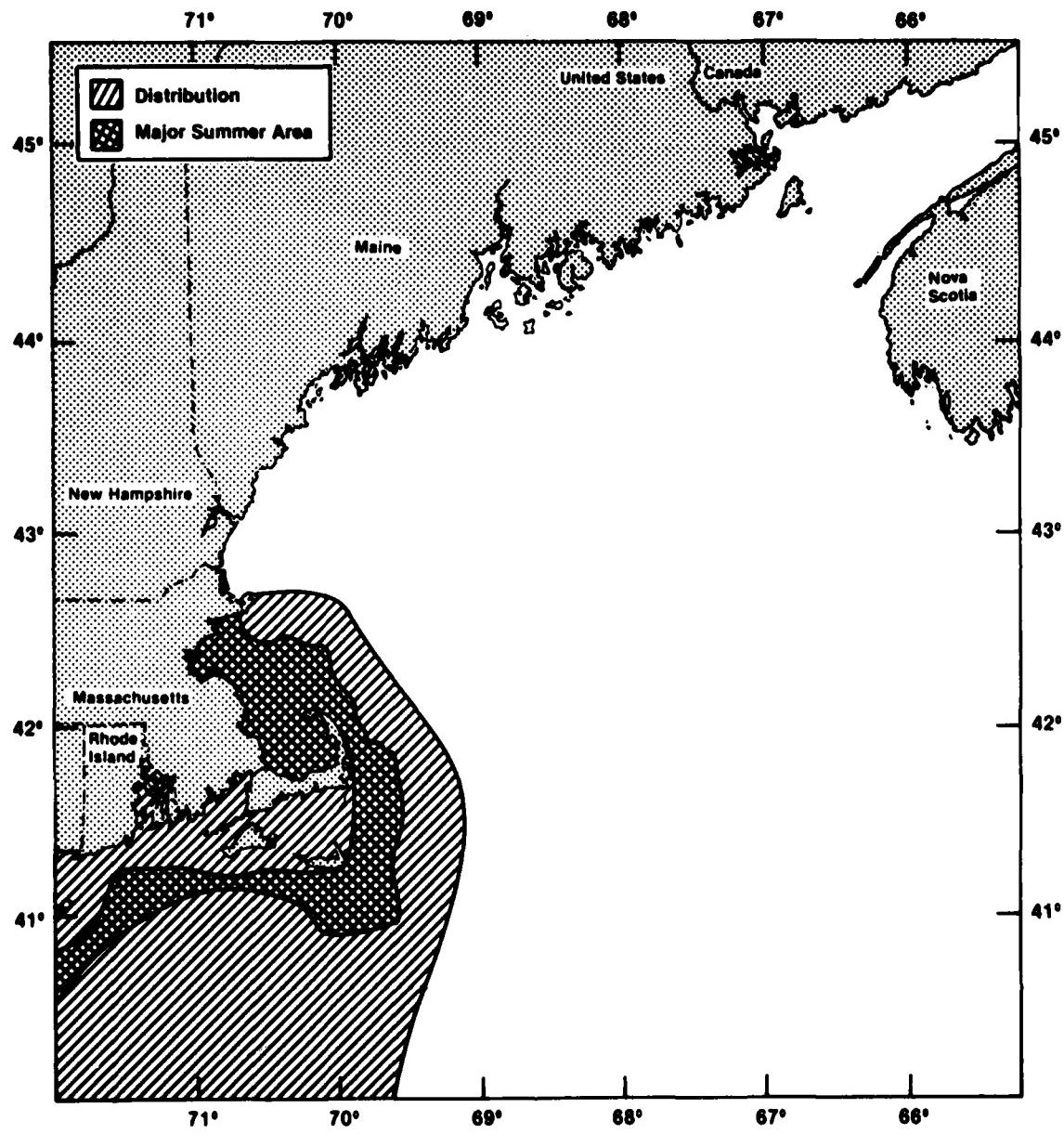


Figure 113.--Scup Distribution (after Ray and Dobbin, 1980).

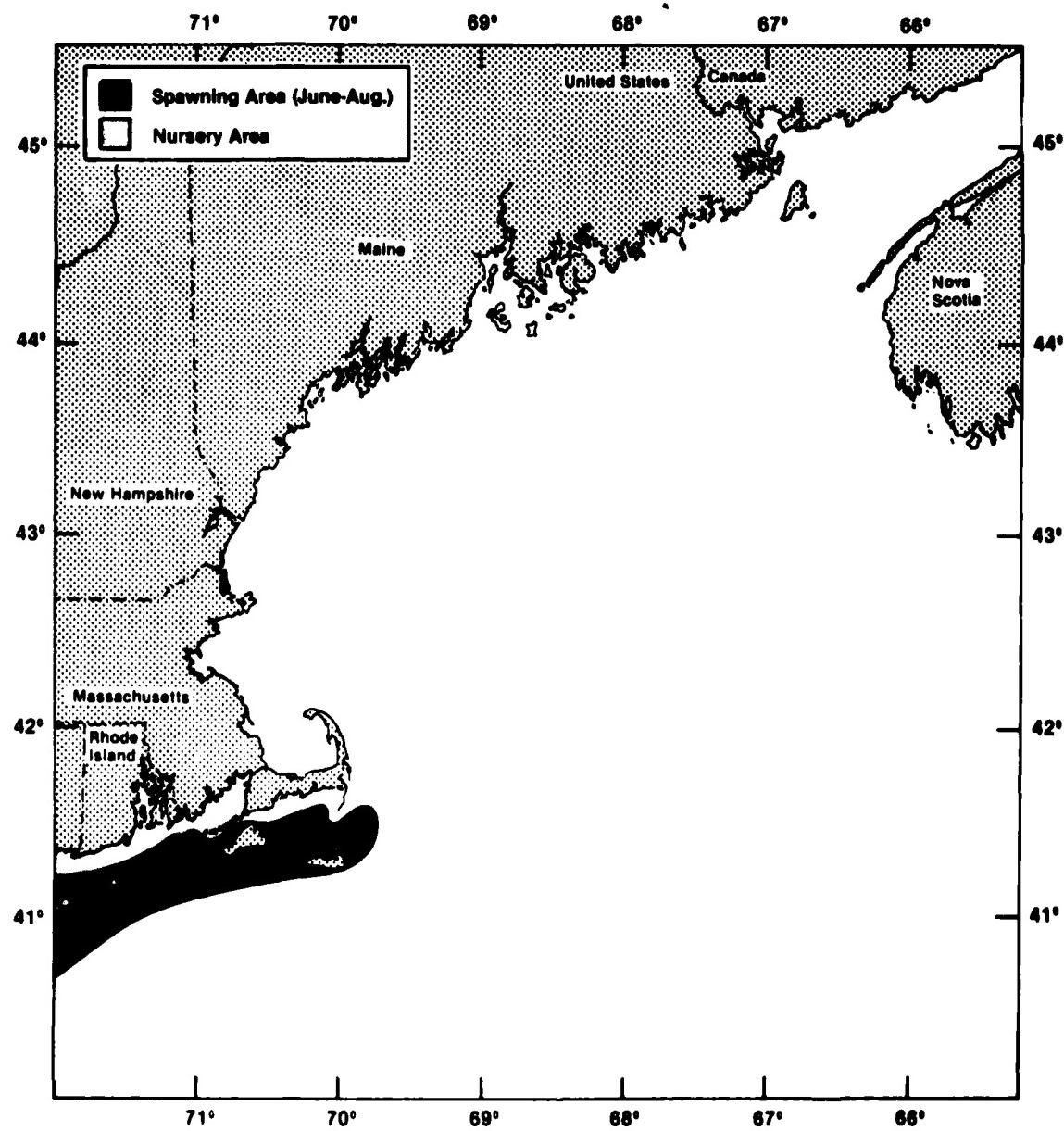


Figure 114.--Scup Spawning Area (after Ray and Dobbin, 1980).

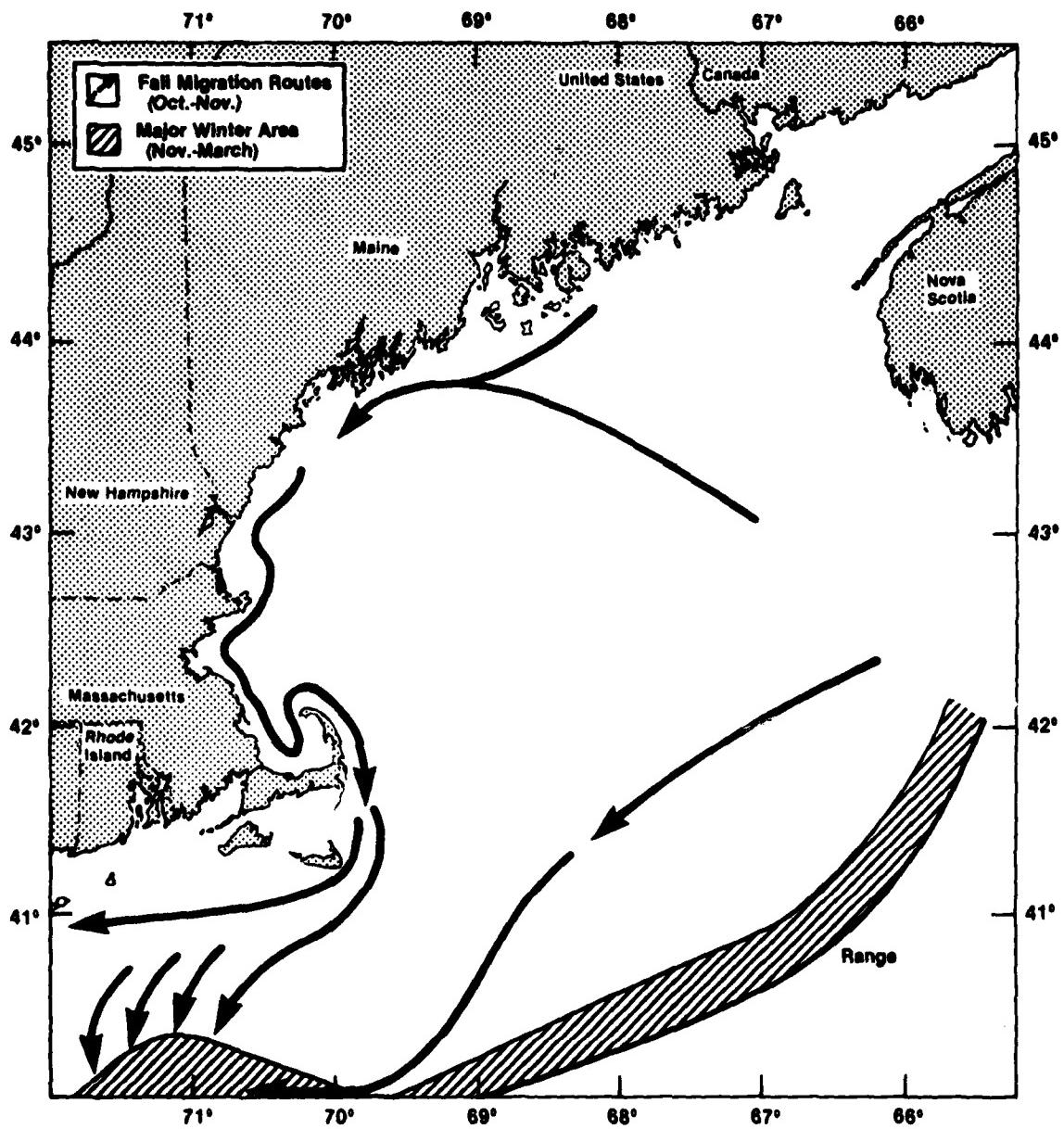


Figure 115.--Atlantic Mackeral Distribution - October to March (after Ray and Dobbin, 1980).

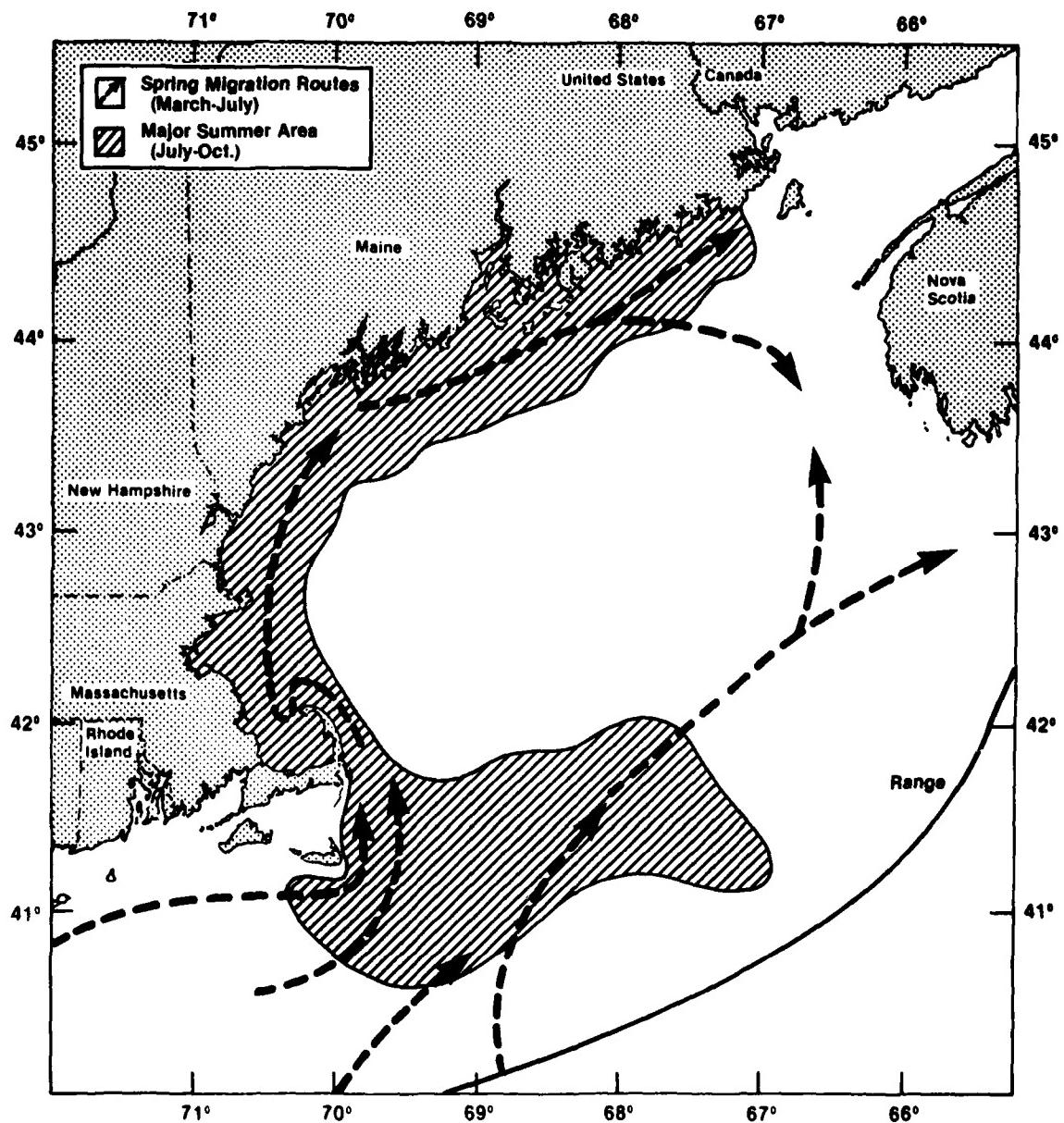


Figure 116.--Atlantic Mackerel Distribution - March to October (after Ray and Dobbin, 1980).

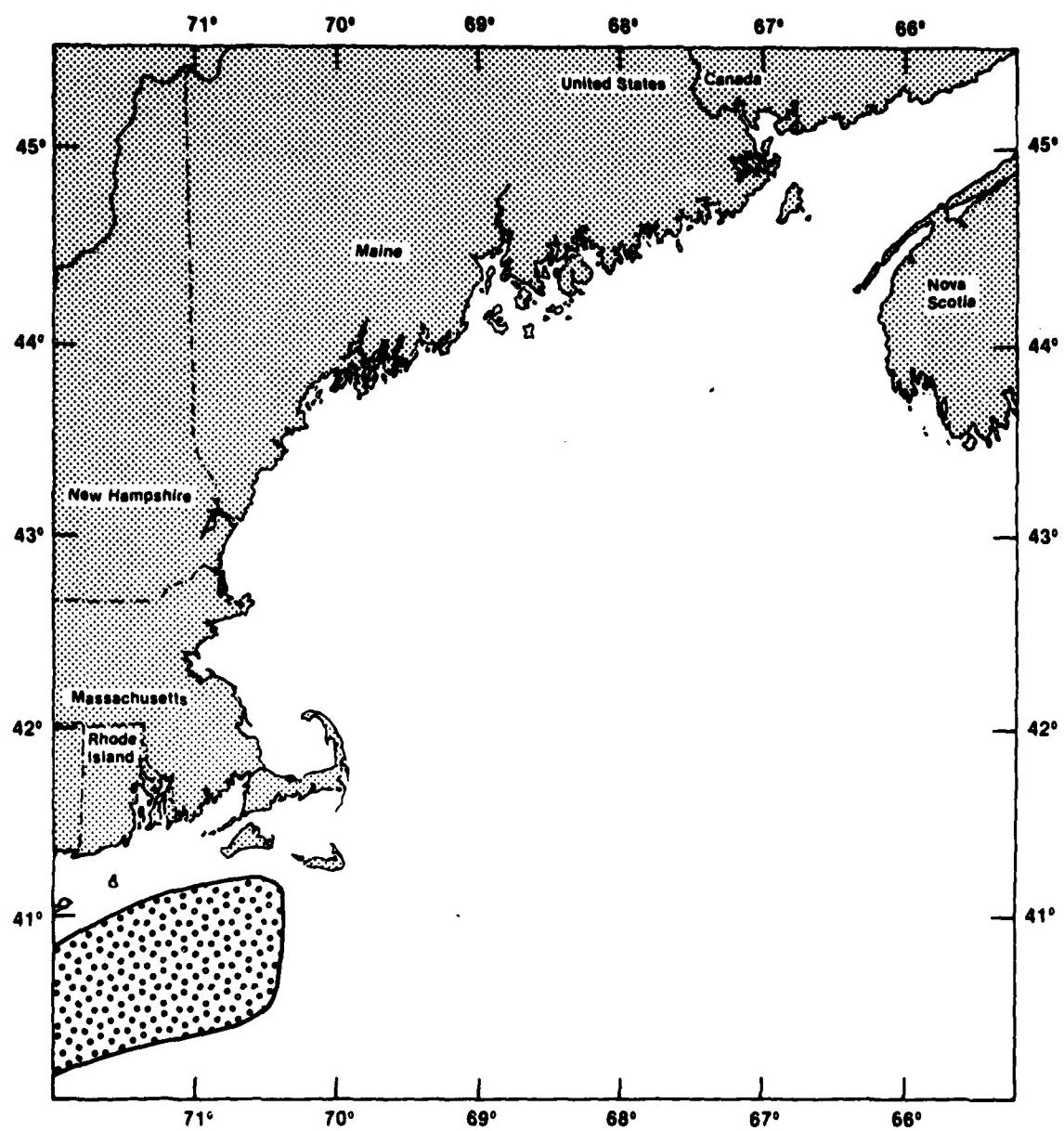


Figure 117.--Atlantic Mackerel Spawning Area (April-June) (after Ray and Dobbin, 1980).

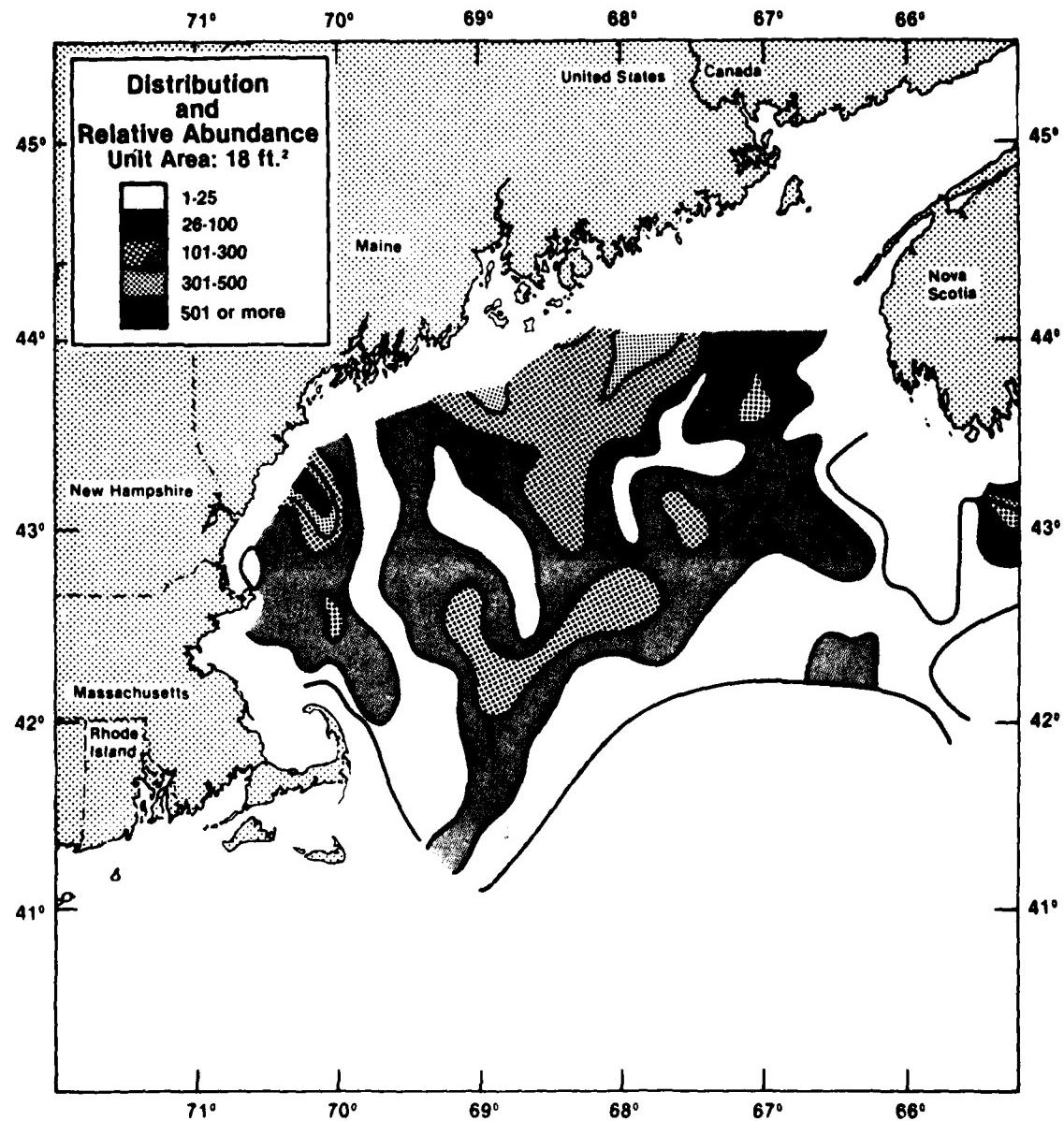


Figure 118.--Redfish Distribution (after Fritz, 1965).

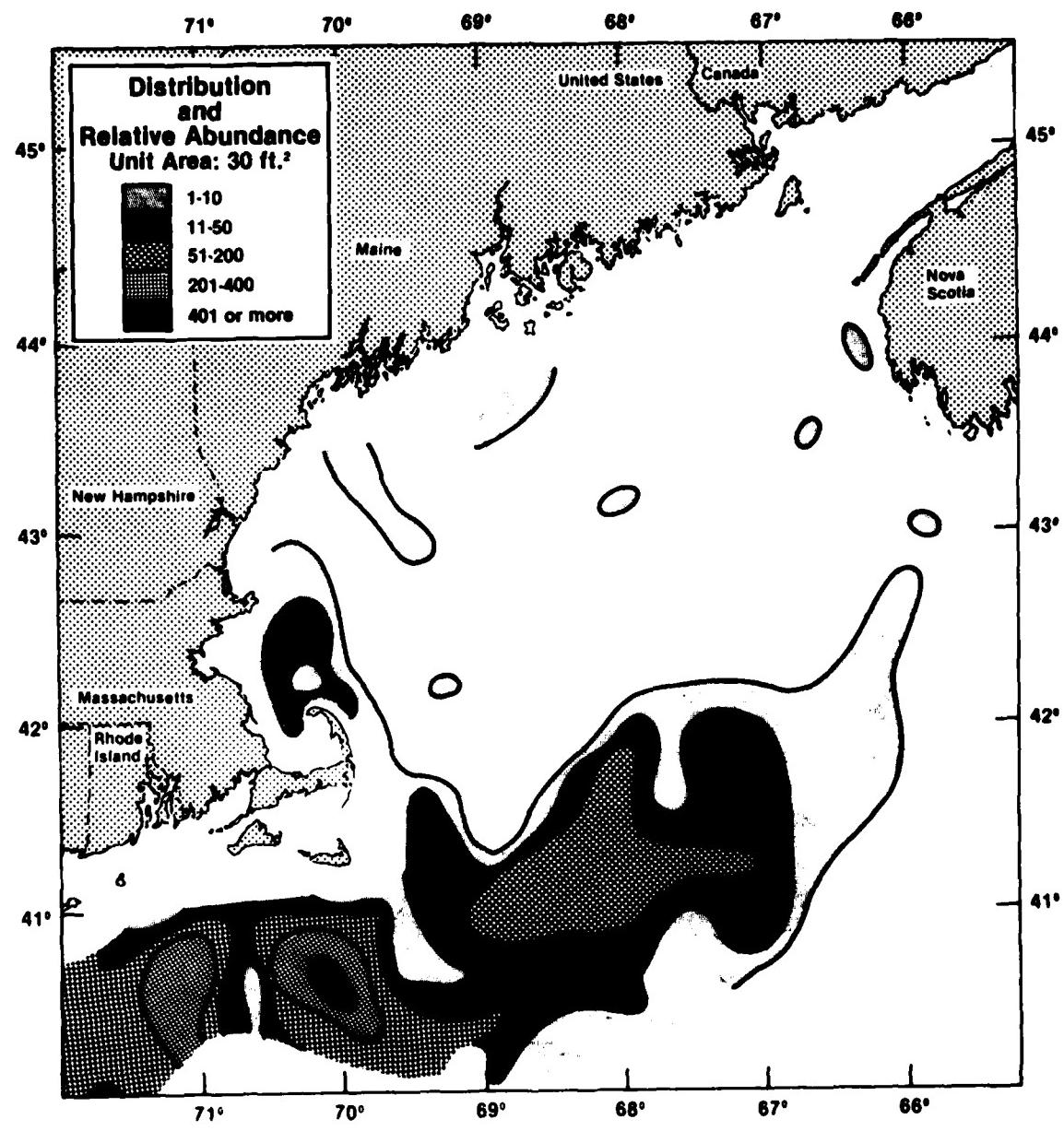


Figure 119.--Butterfish Distribution (after Fritz, 1965).

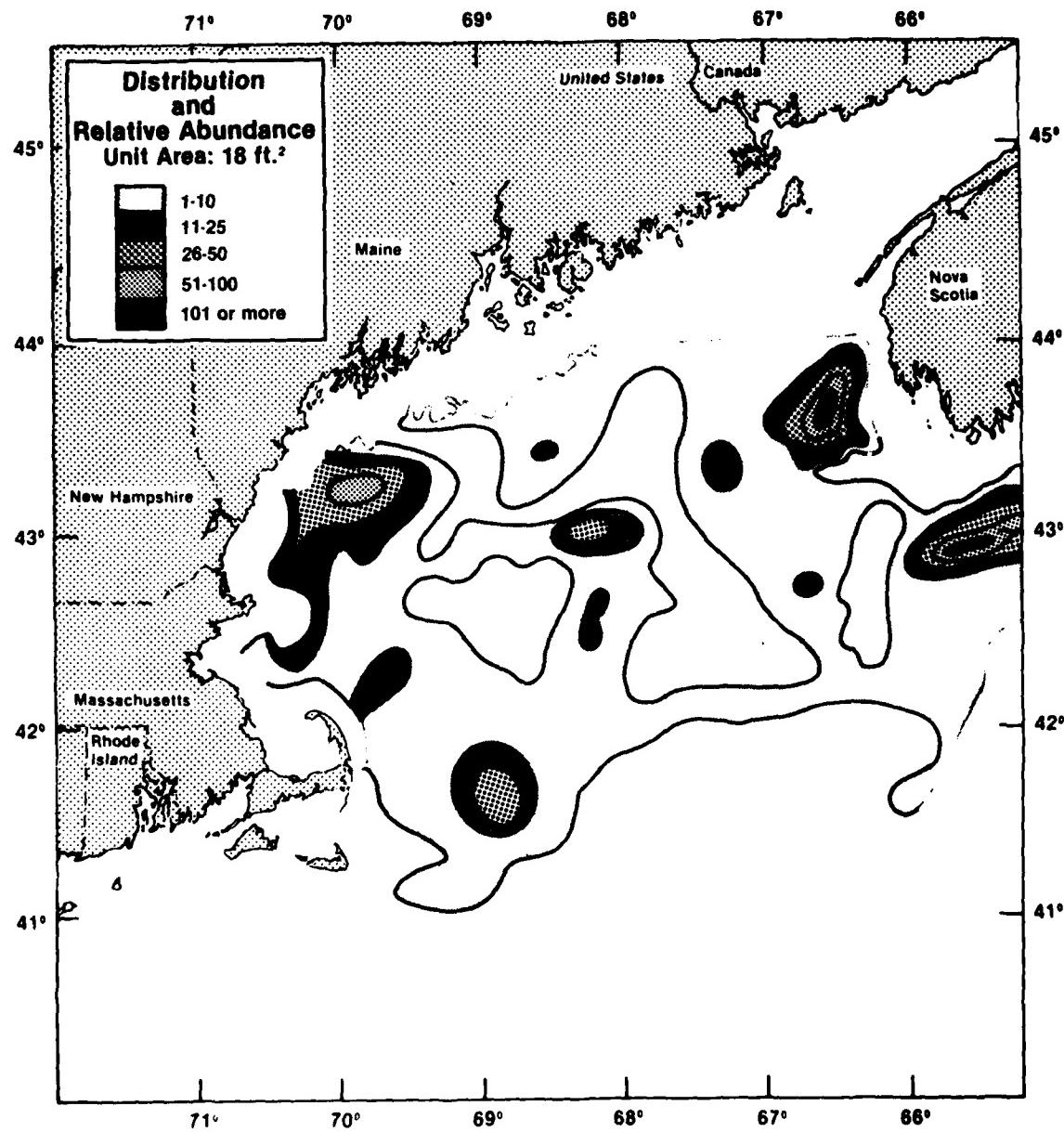


Figure 120.--American Pollock Distribution (after Fritz, 1965).

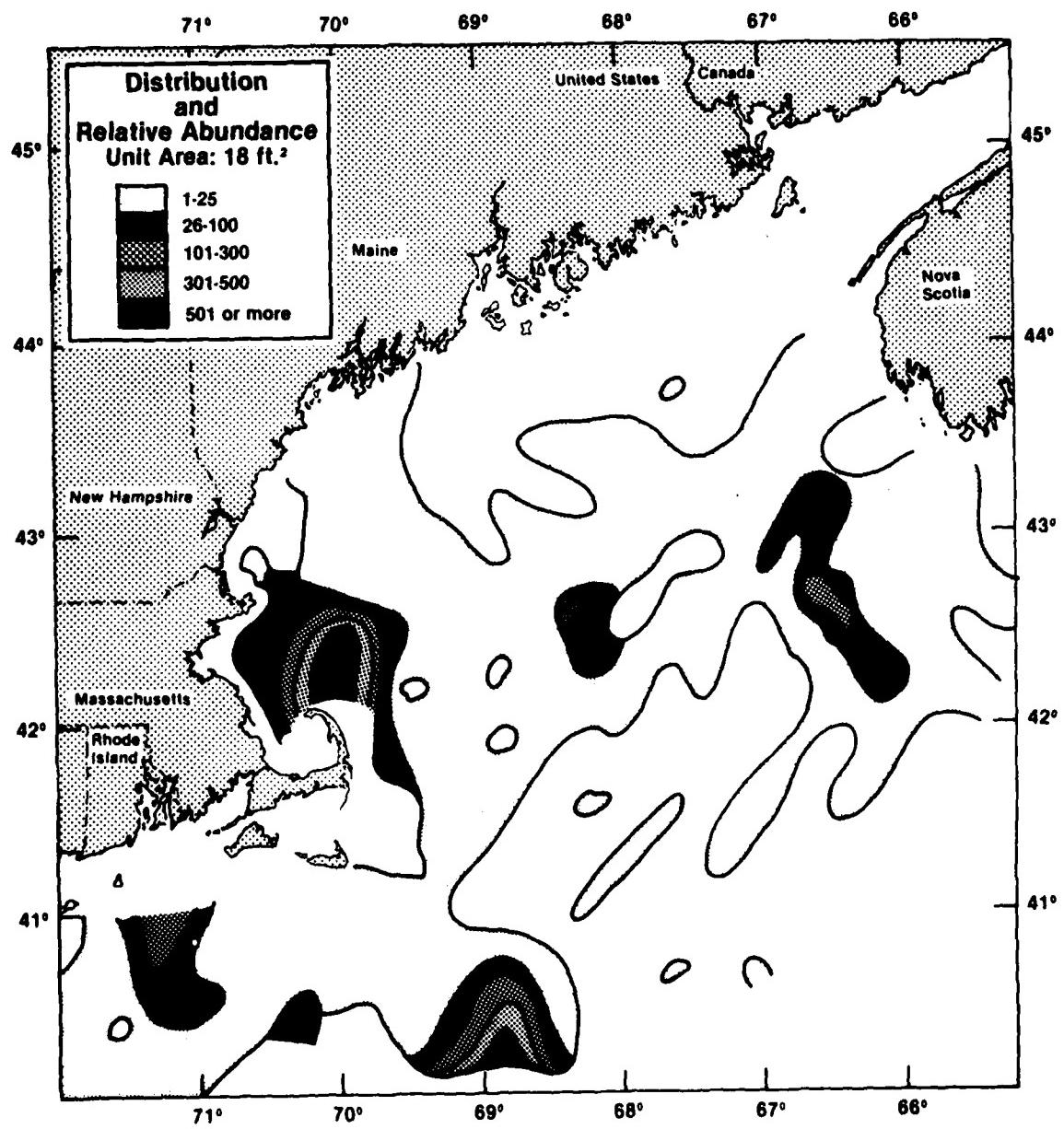


Figure 121.--Spiny Dog Fish Distribution (after Fritz, 1965).

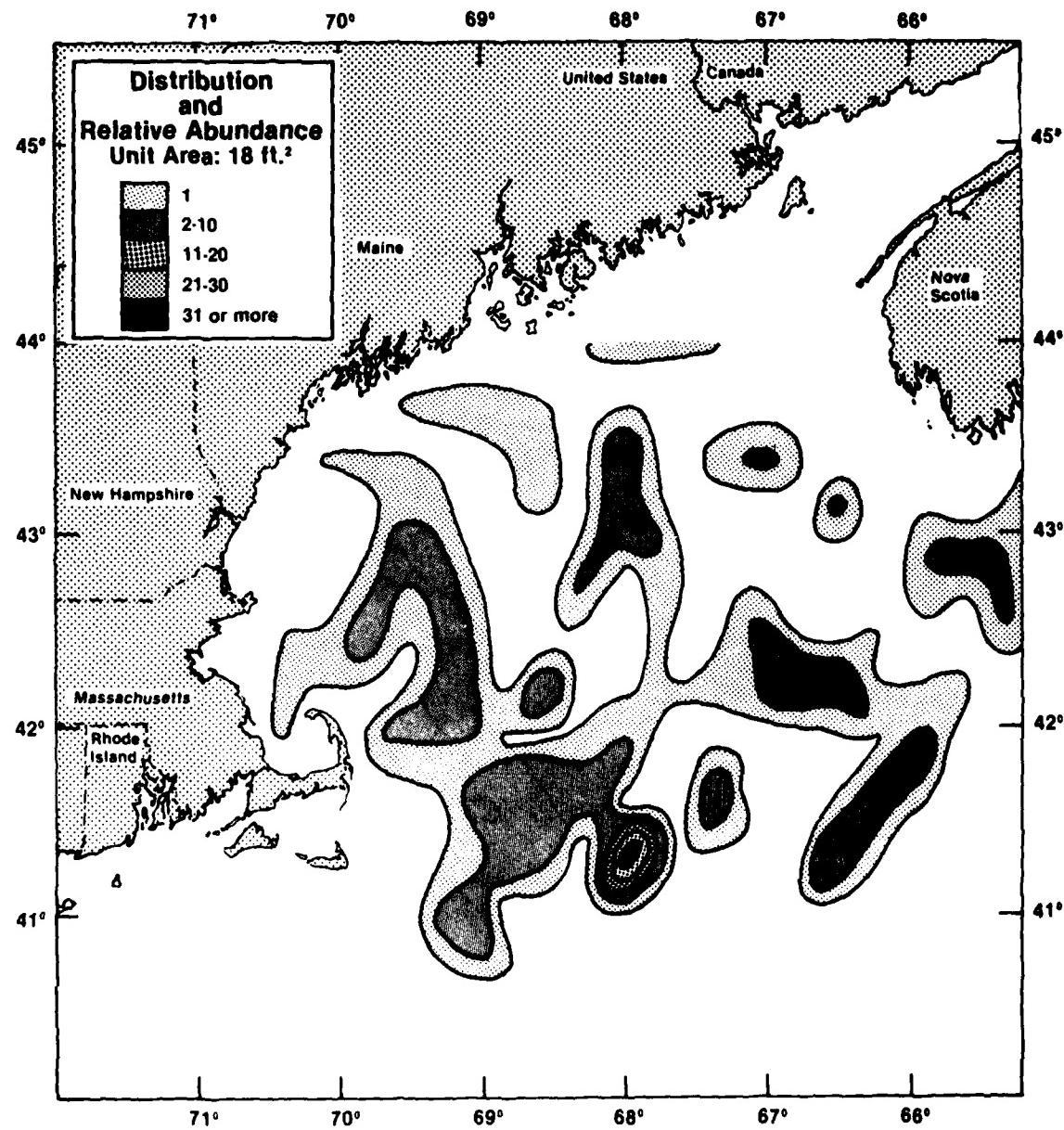


Figure 122.--Thorny Skate Distribution (after Fritz, 1965).

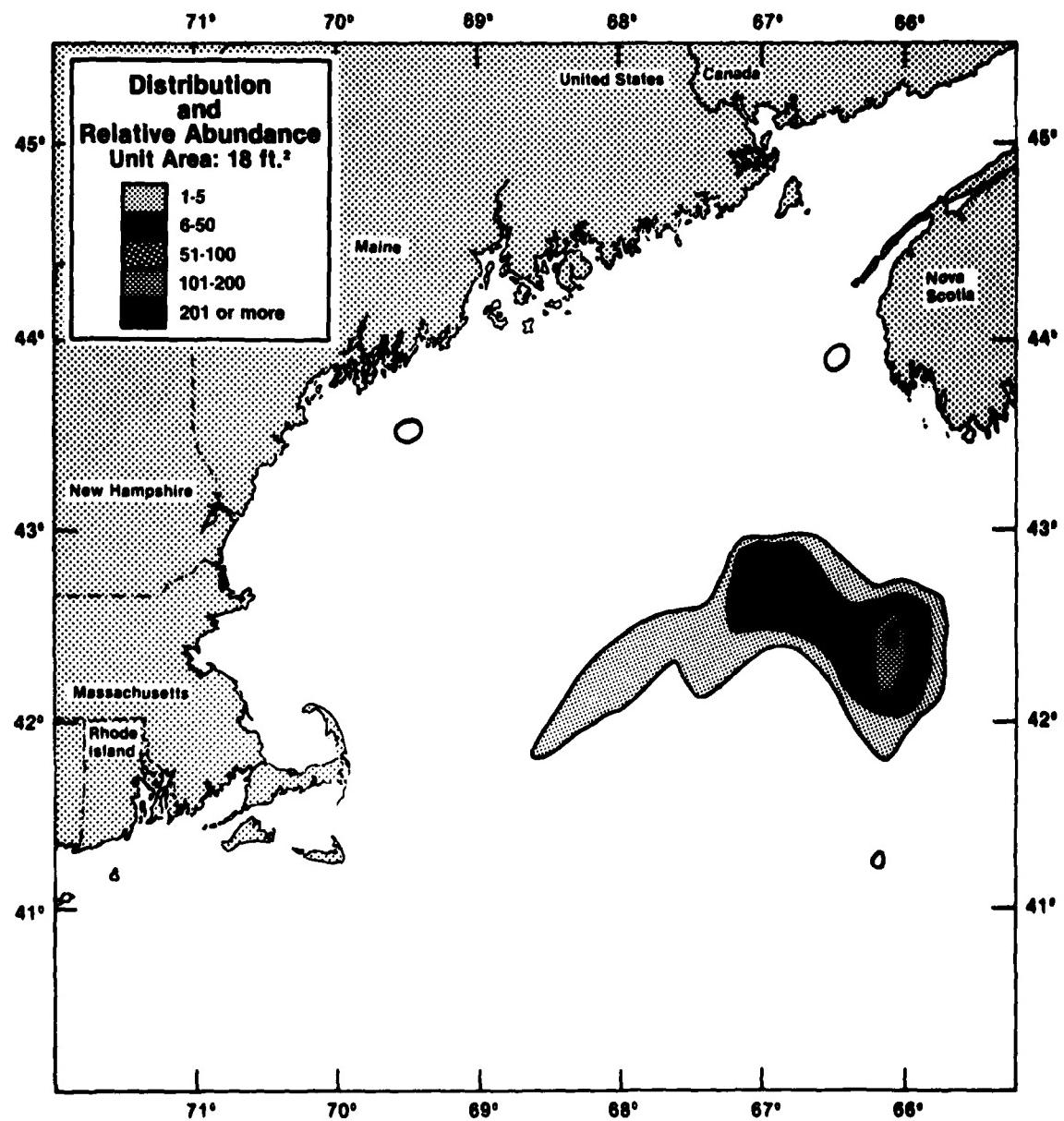


Figure 123.--Argentine Distribution (after Fritz, 1965).

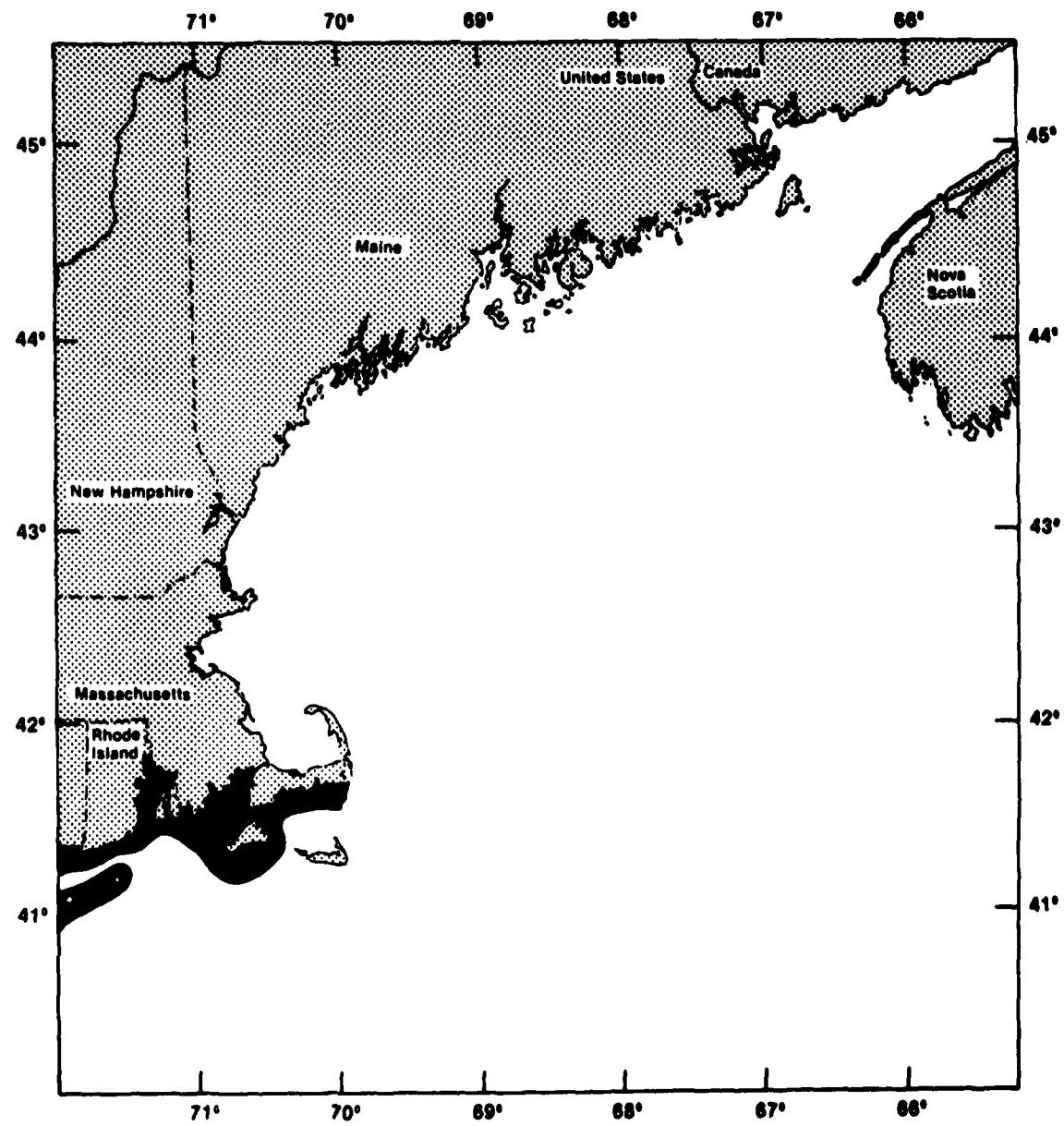


Figure 124.--Brown Shrimp Distribution (after Ray and Dobbin, 1980).

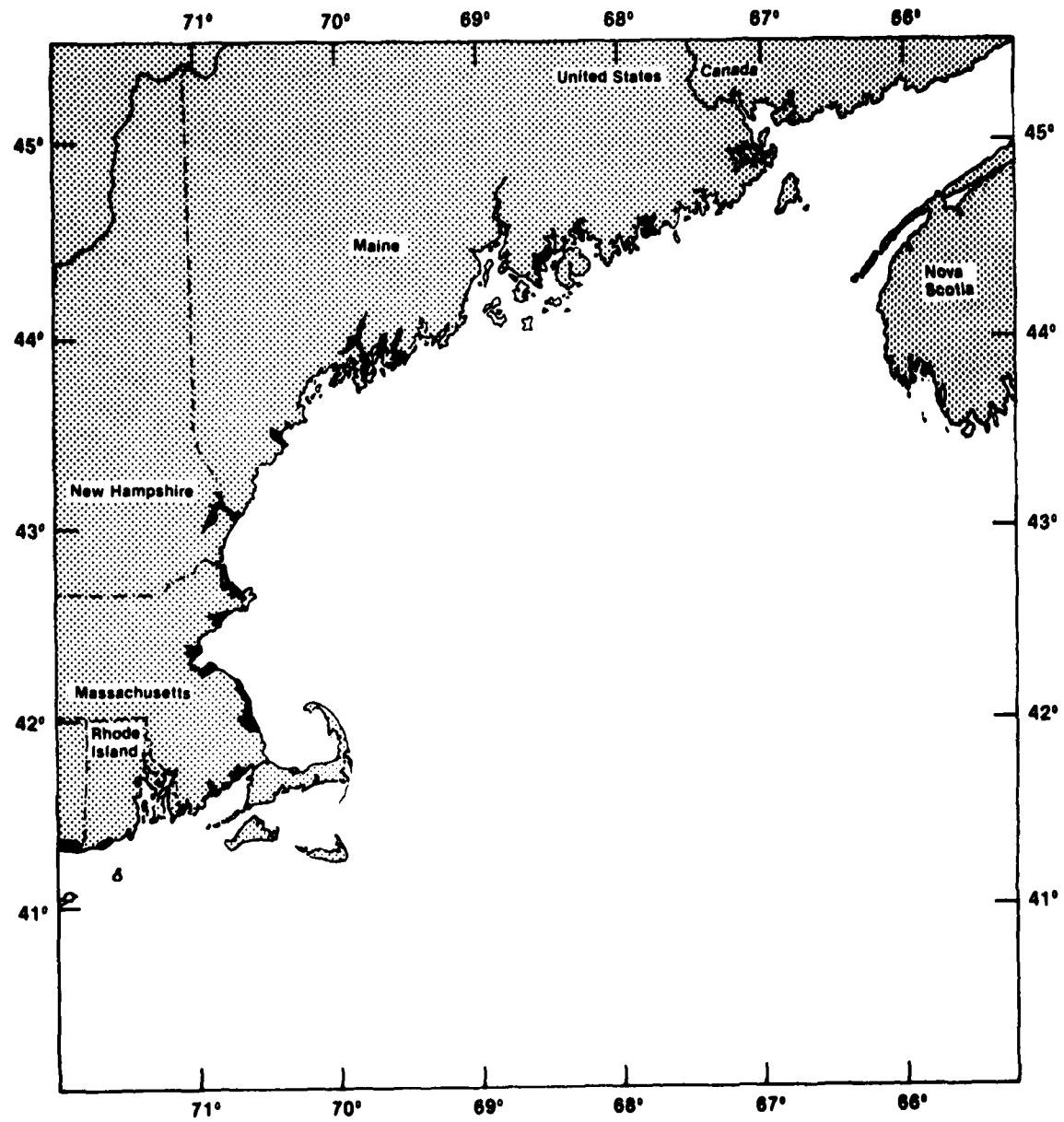


Figure 125.--American Smelt Distribution (after Freeman and Walford - I, II, 1974).

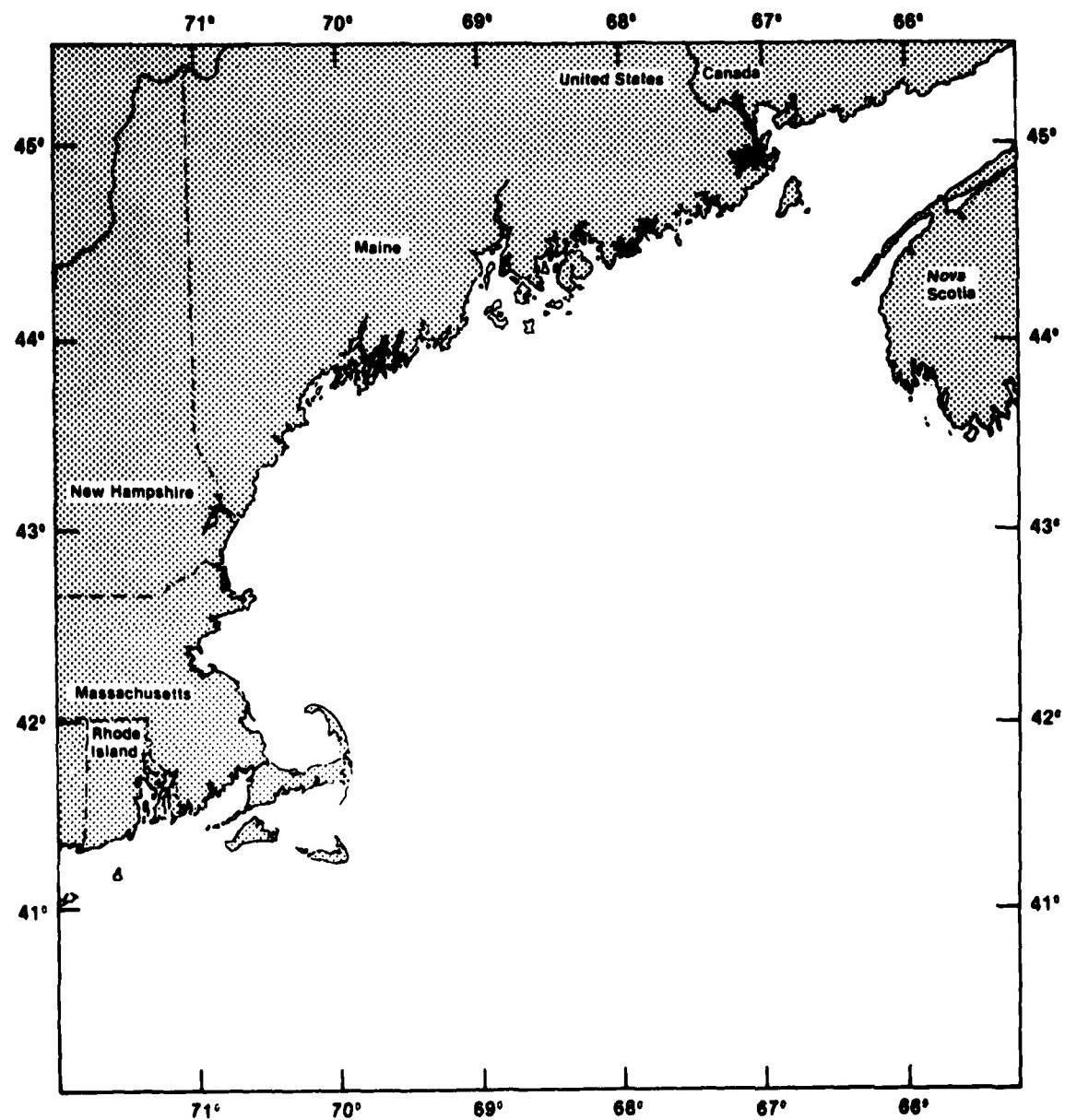


Figure 126.--Atlantic Salmon Distribution (after Freeman and Walford, 1974).

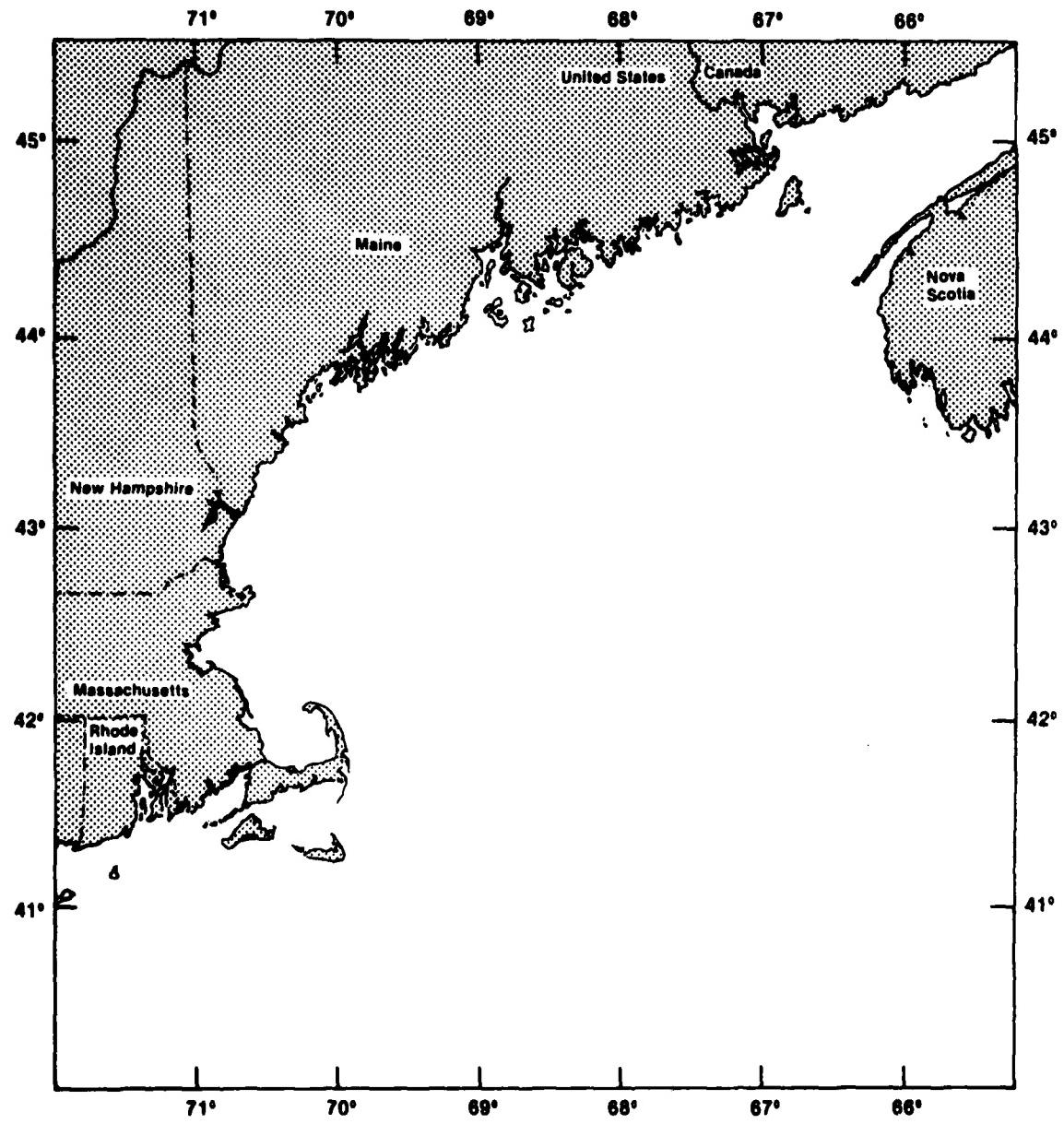


Figure 127.--White Perch Distribution (after Freeman and Walford, 1974).

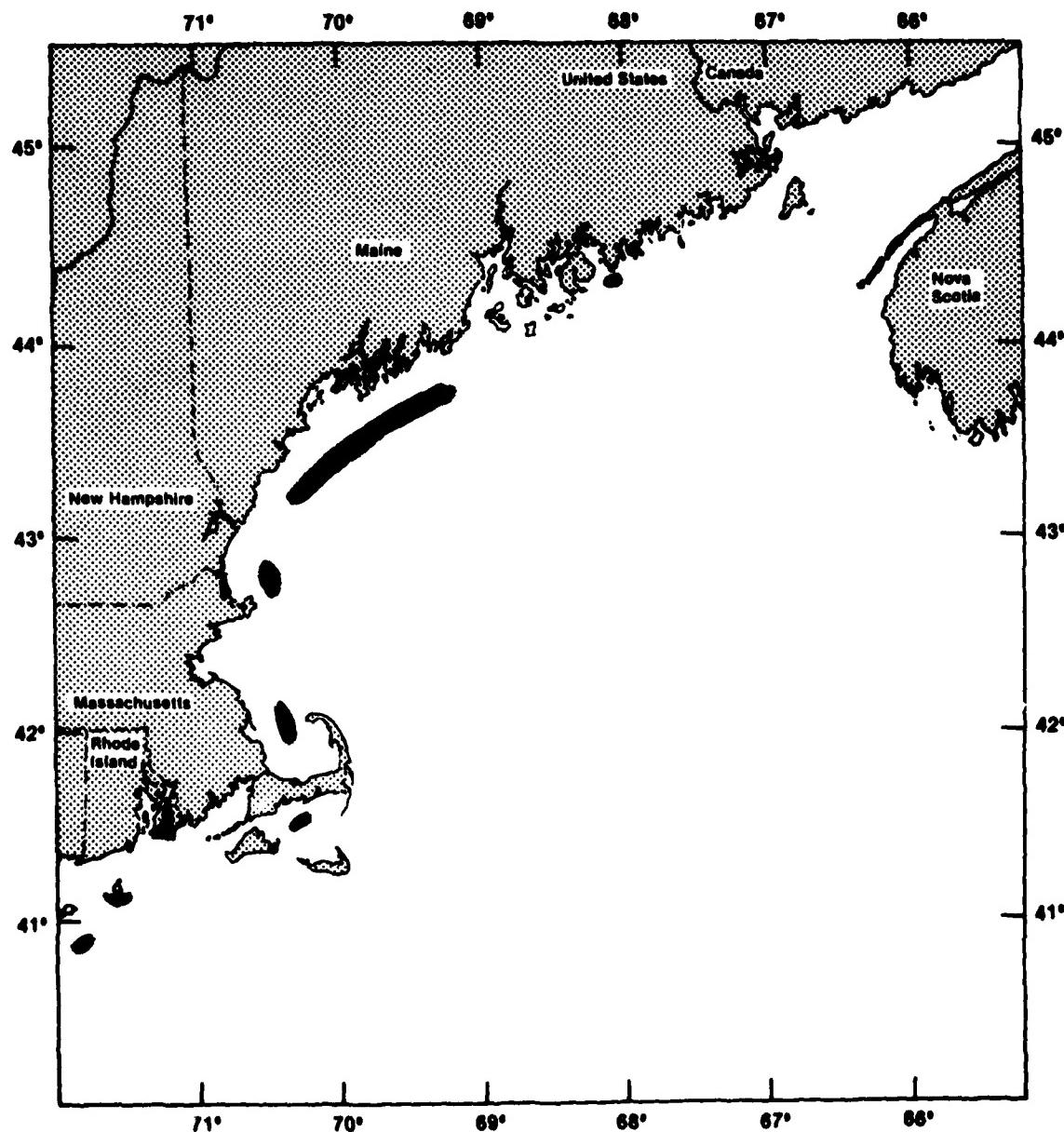


Figure 128.--Cunner Distribution (after Freeman and Walford, 1974).

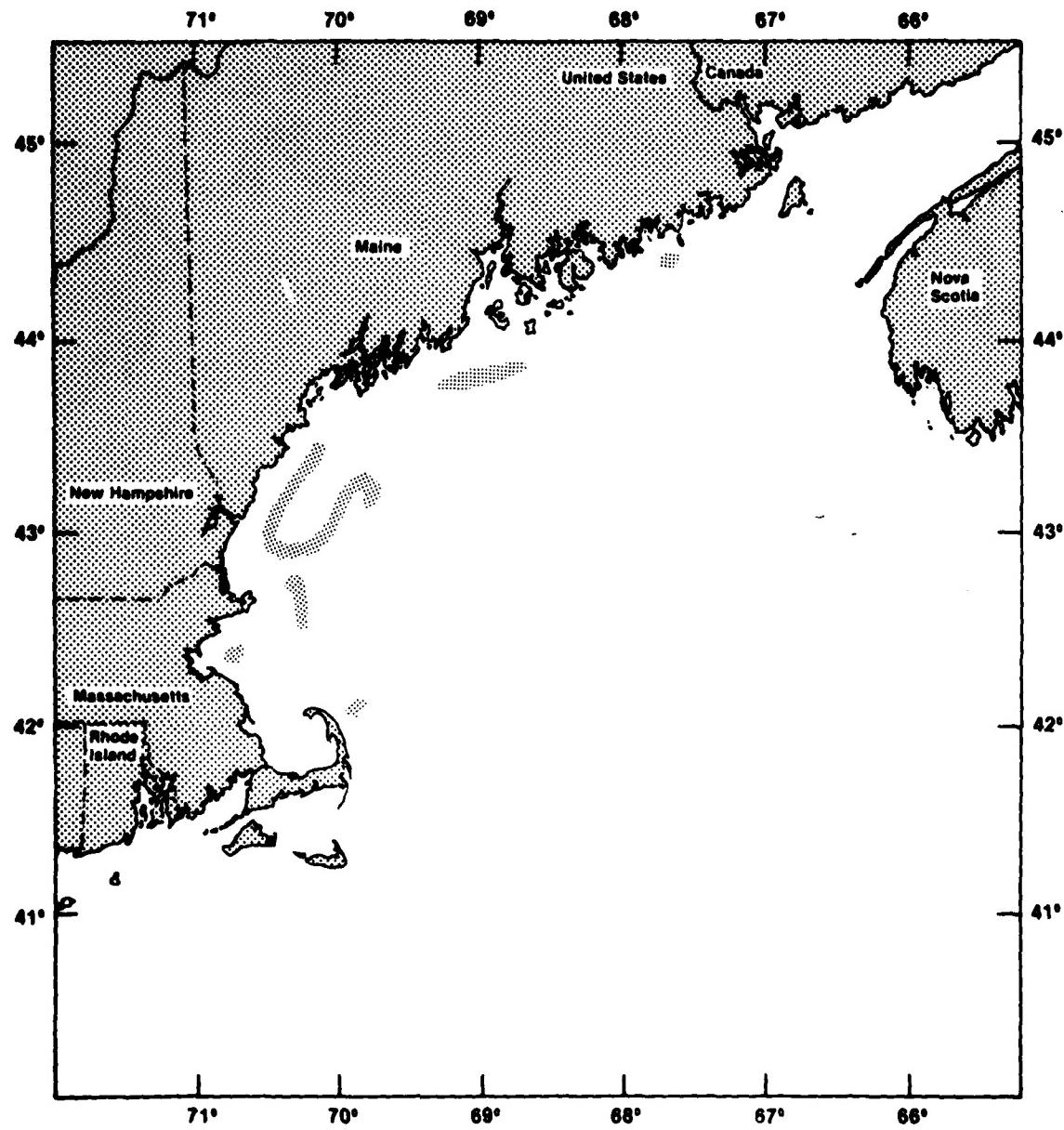


Figure 129.--Cusk Distribution (after Freeman and Walford, 1974).

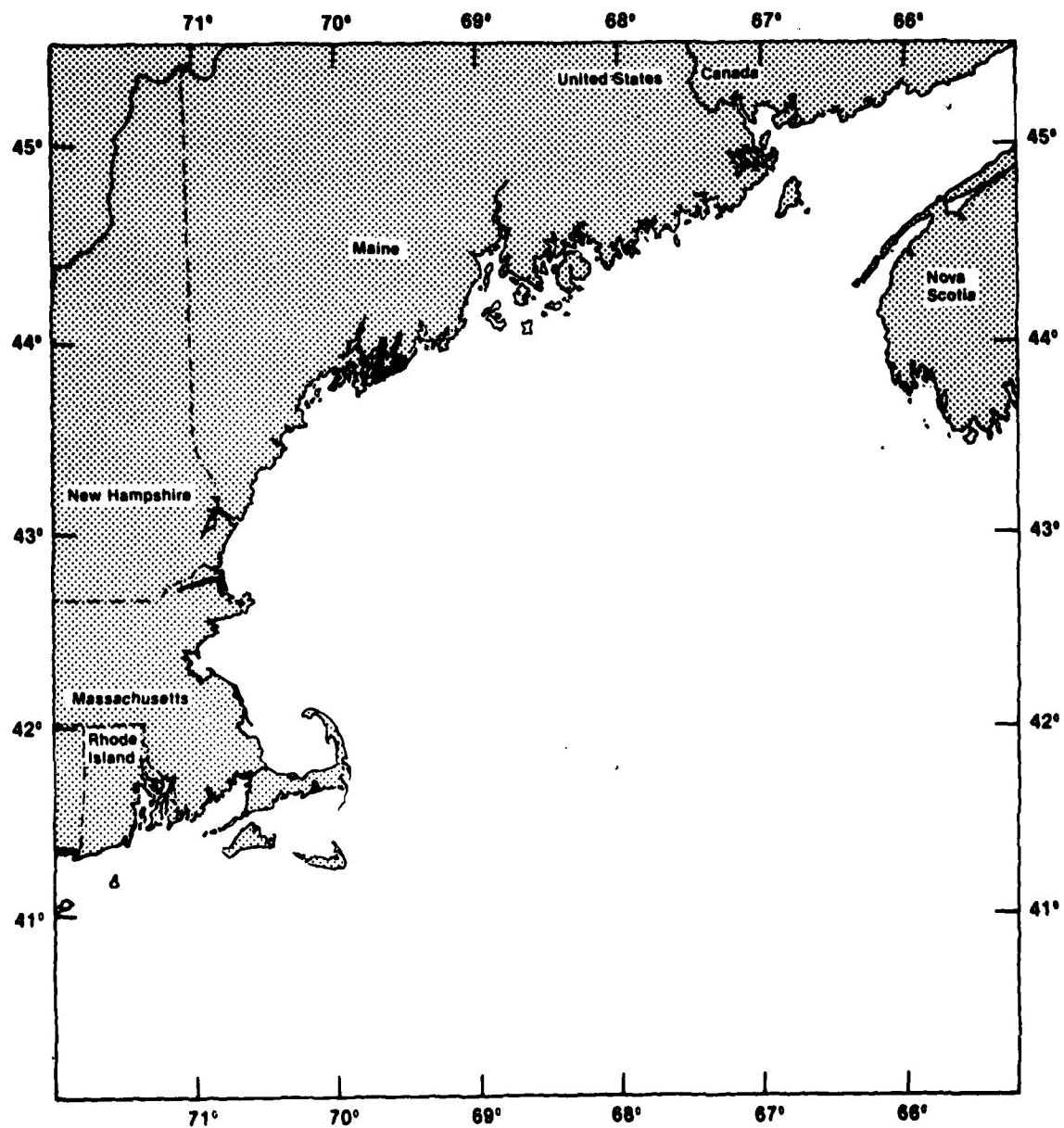


Figure 130.--Atlantic Tomcod Distribution (after Freeman and Walford, 1974).

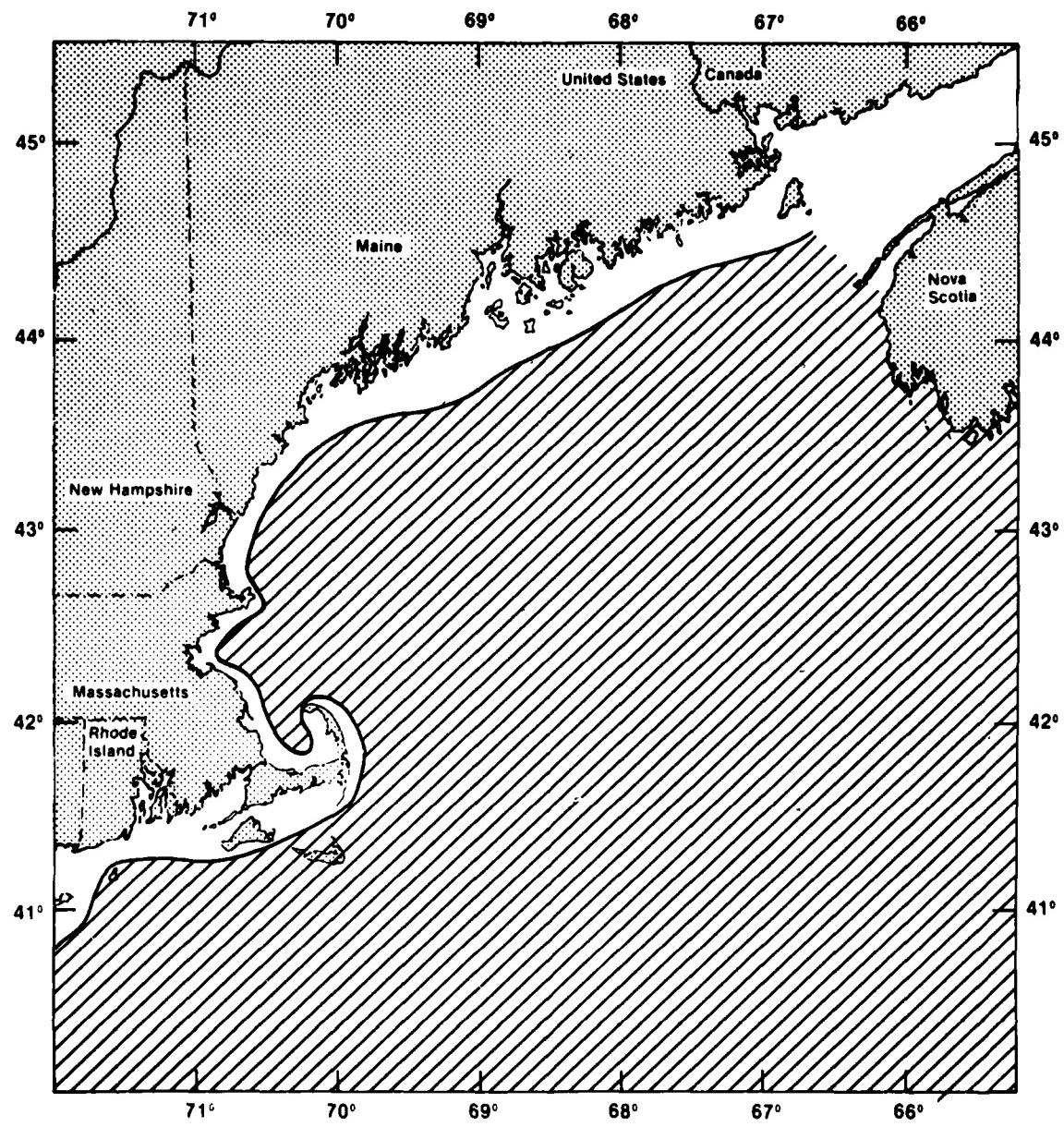


Figure 131.--Bluefin Tuna Distribution (summer concentration > 150 kg fish) (after Ray and Dobbin, 1980)

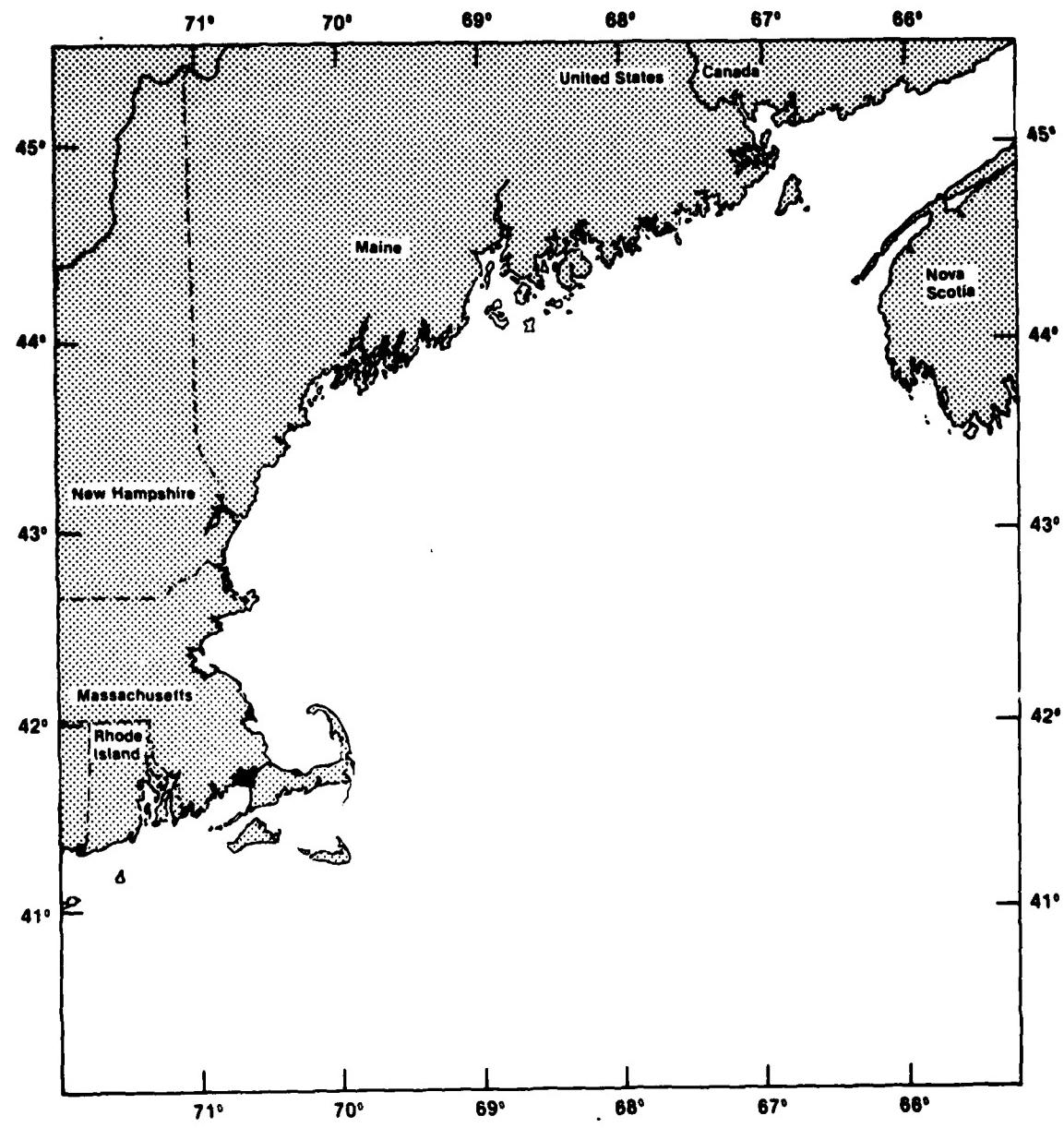


Figure 132.--Freshwater Eel Distribution (after Freeman and Walford, 1974).

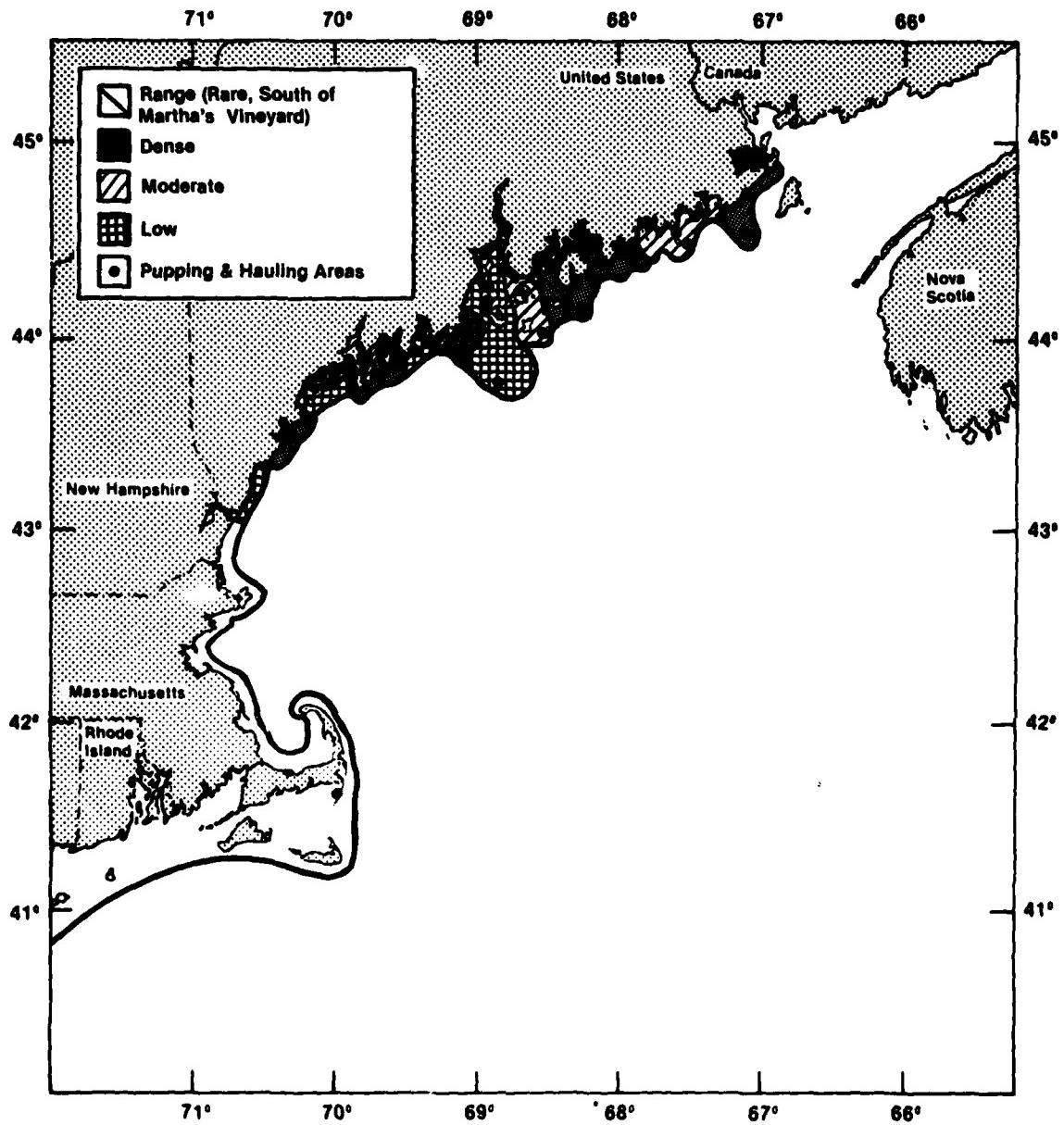


Figure 133.--Harbor Seal Distribution (after Ray and Dobbin, 1980).

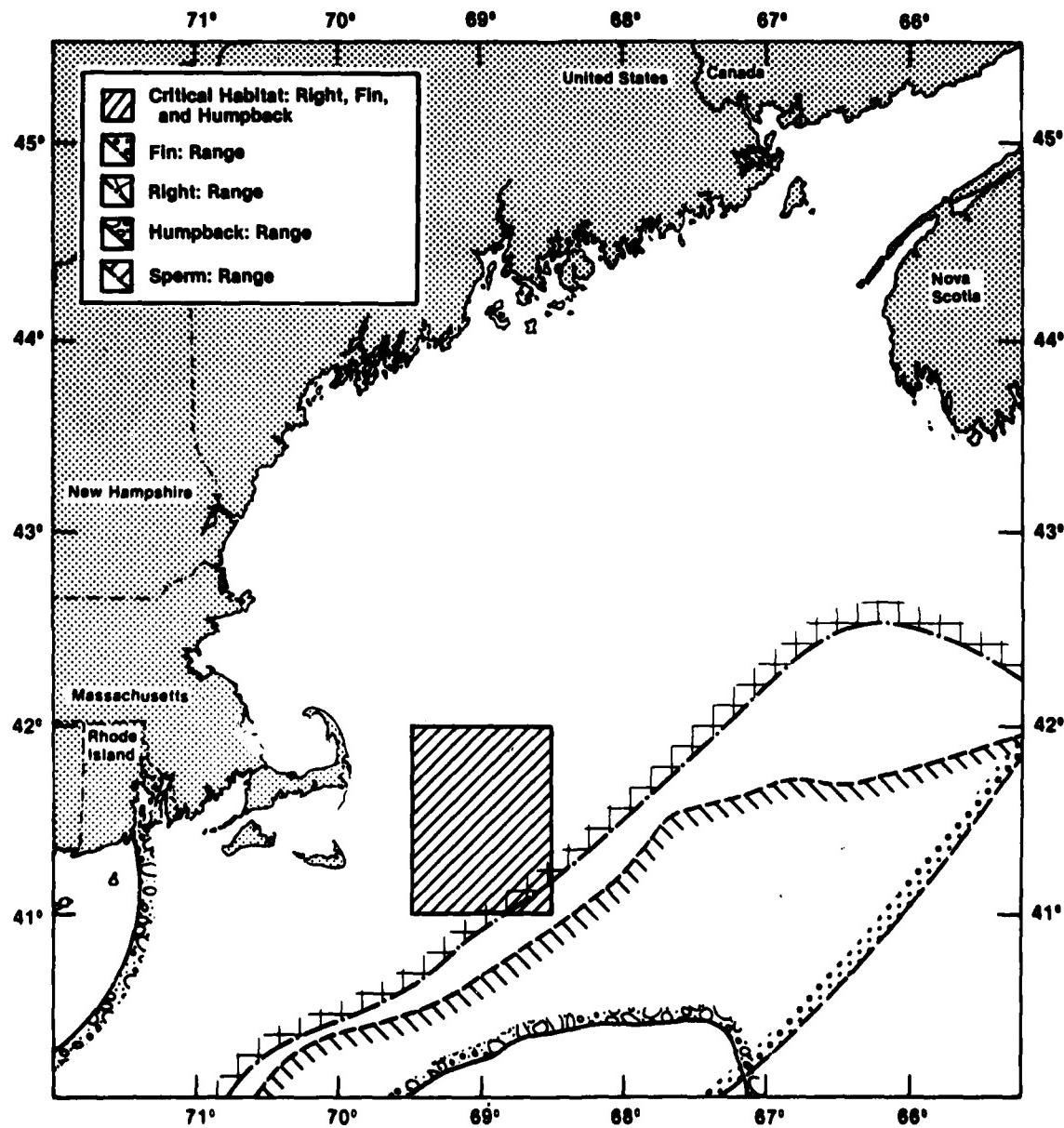


Figure 134.—Whale Distribution (after Ray and Dobbin, 1980).

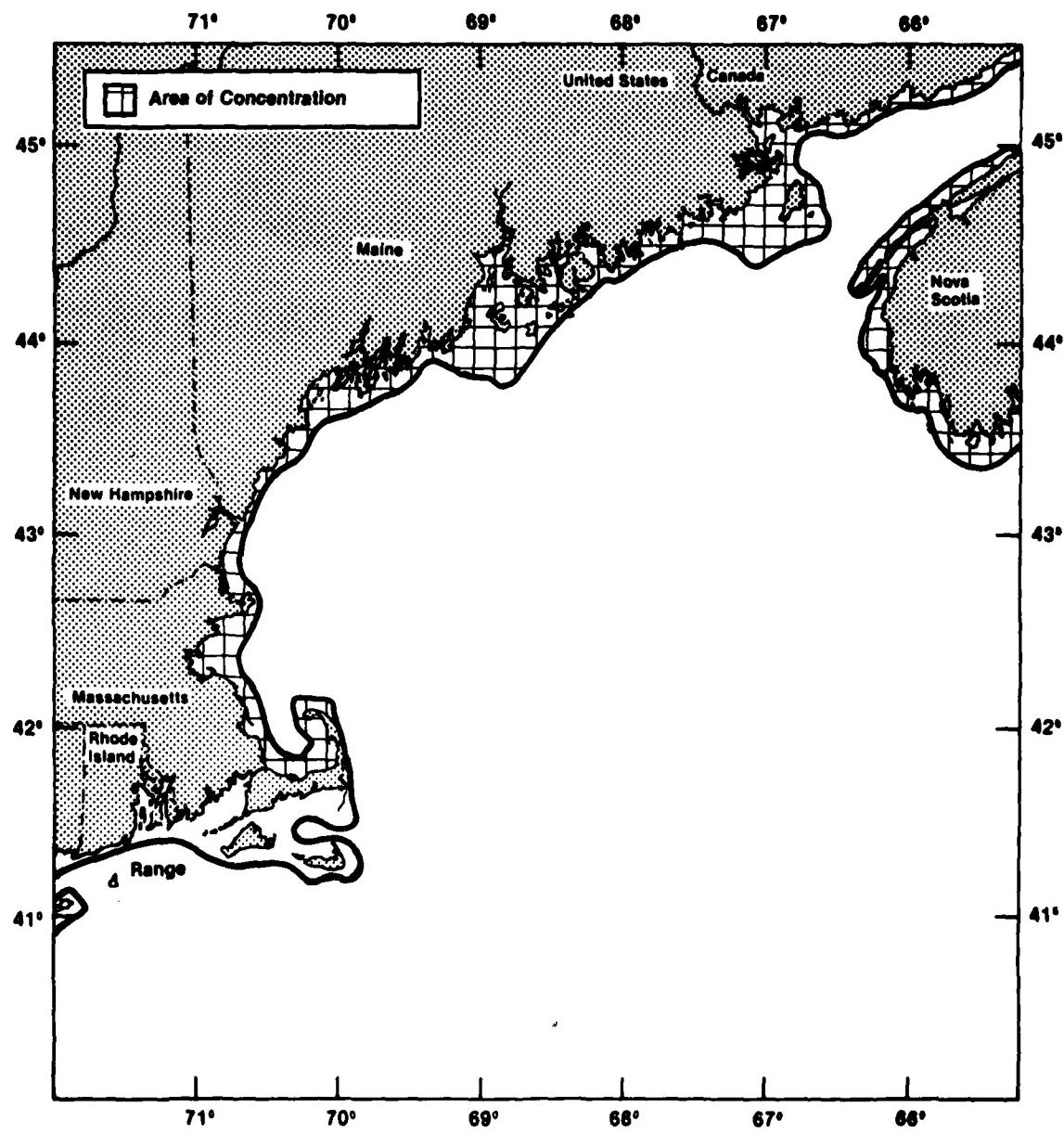


Figure 135.--Harpor Porpoise Distribution (after Ray and Dobbin, 1980).

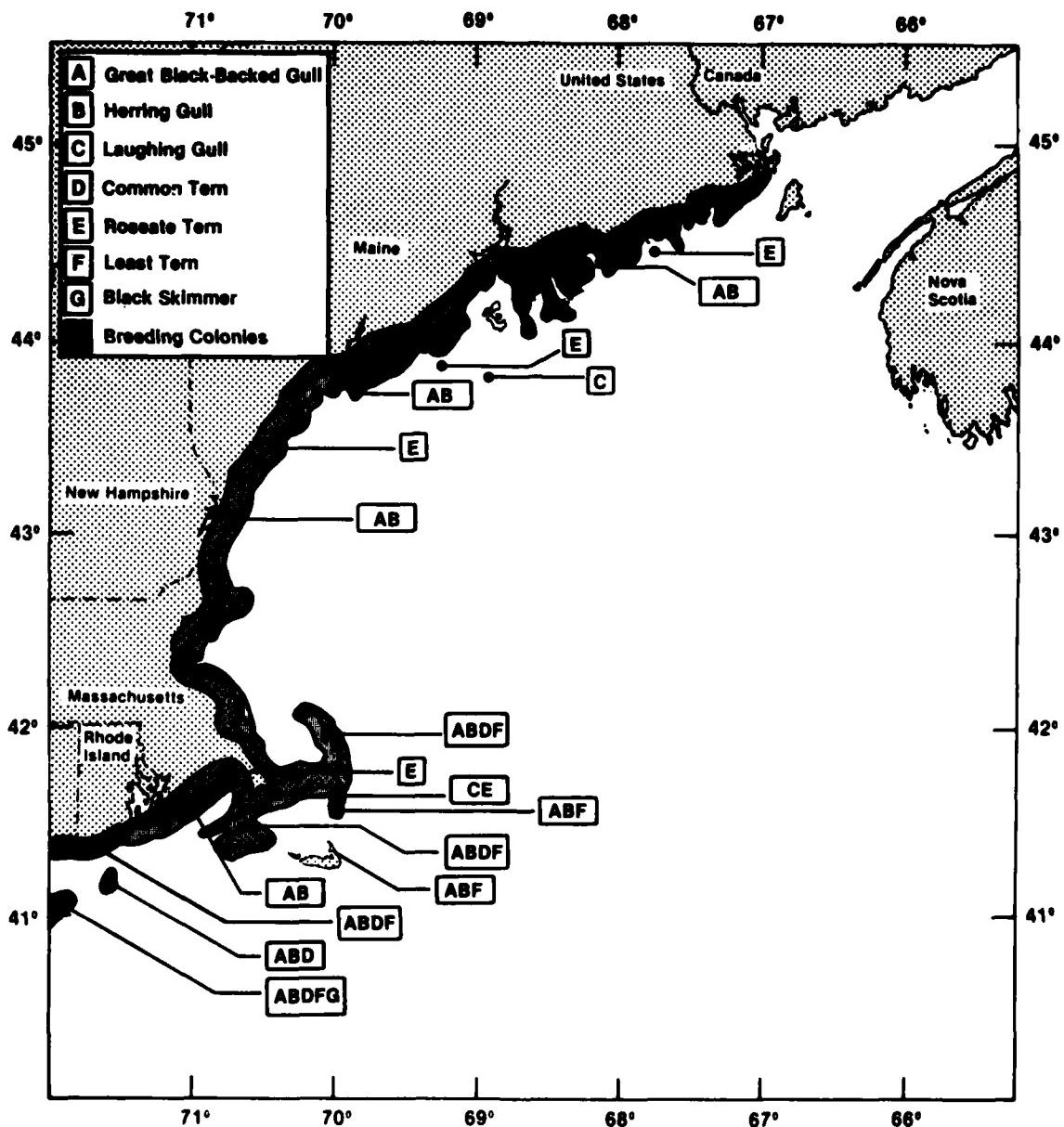


Figure 136.--Gulls, Terns, and Skimmers: Breeding Distribution (after Ray and Dobbin, 1980).

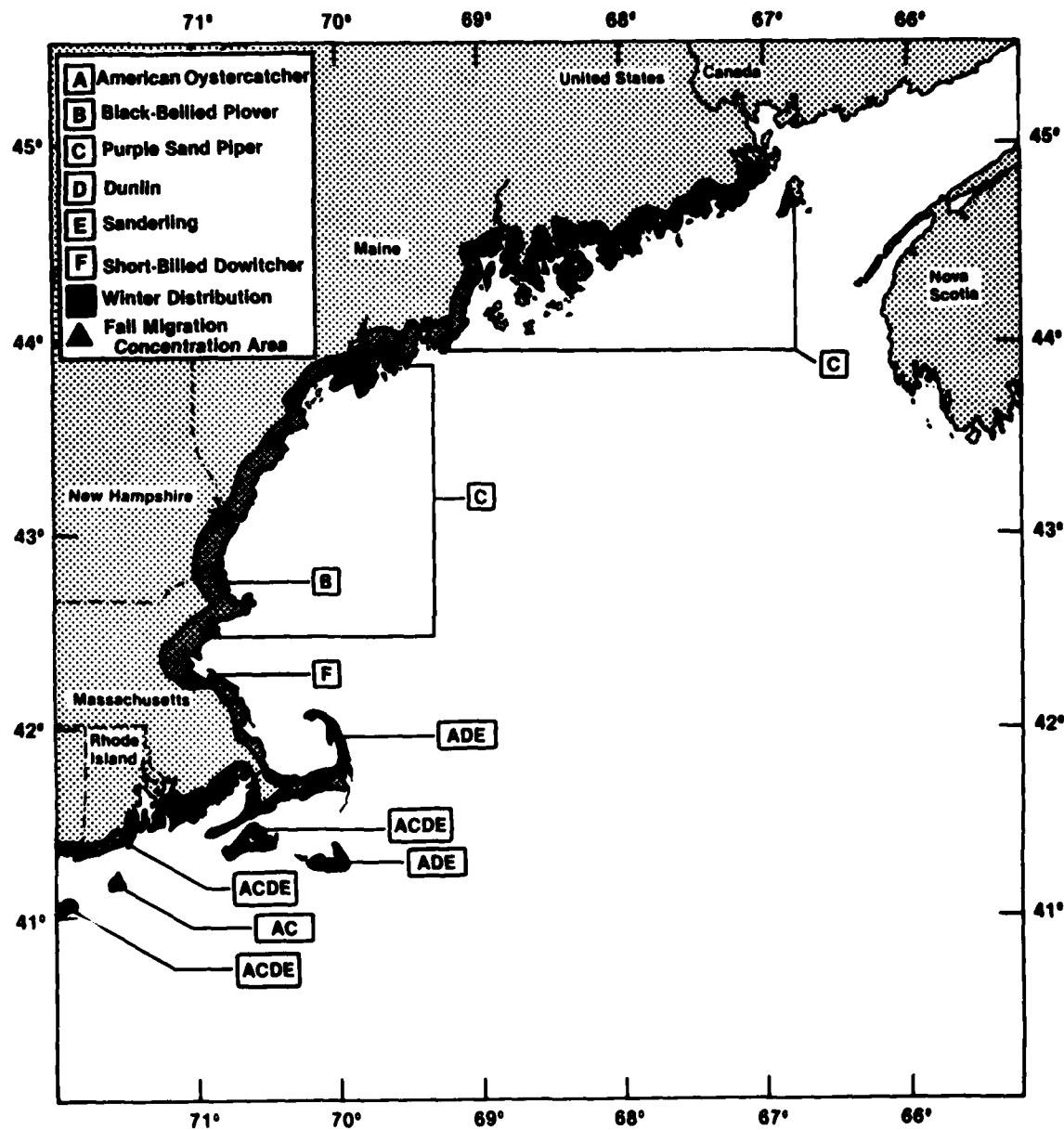


Figure 137.--Shorebirds: Winter Distribution (after Ray and Dobbin, 1980).

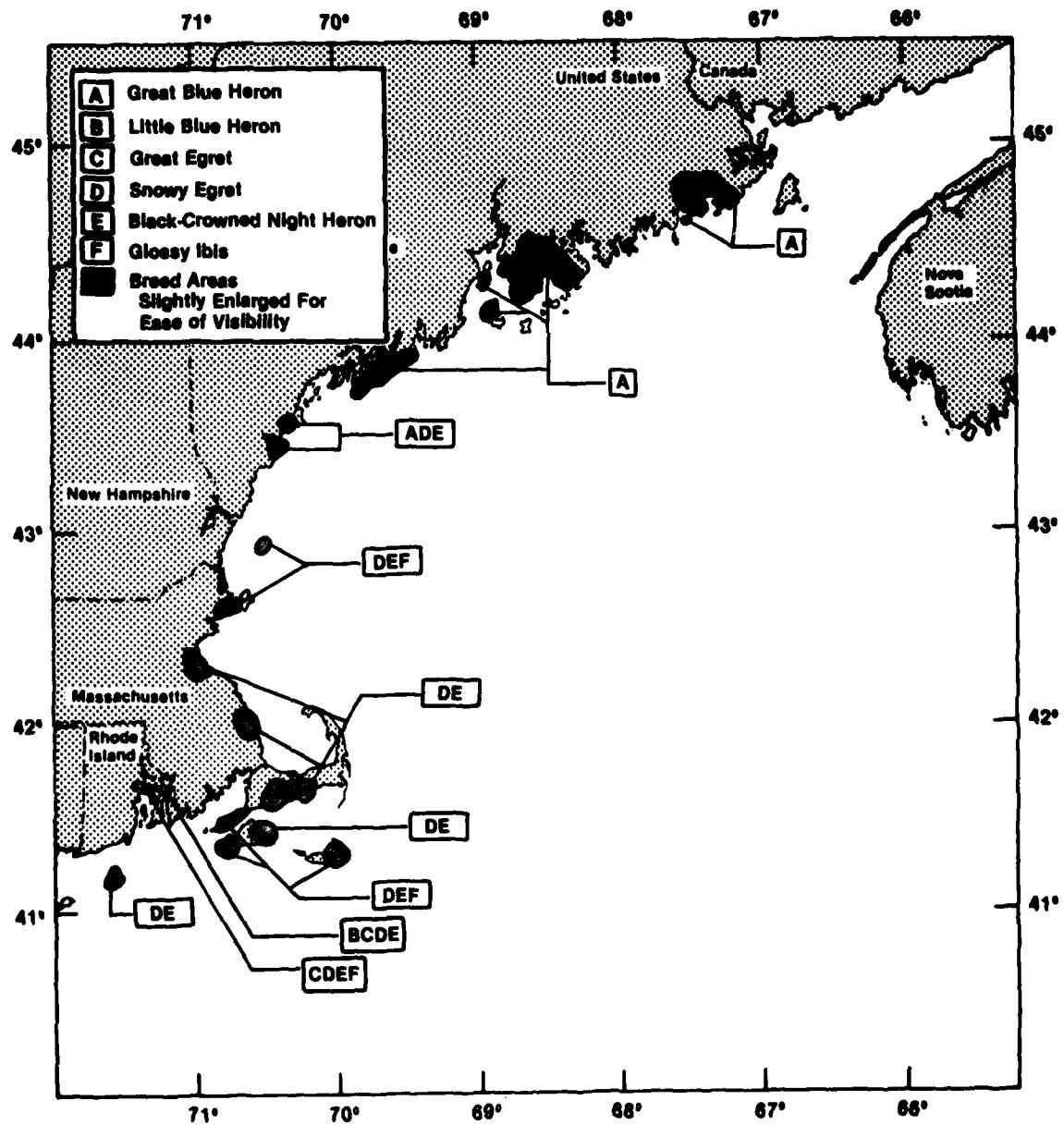


Figure 138.--Waders: Breeding Colonies (after Ray and Dobbin, 1980).

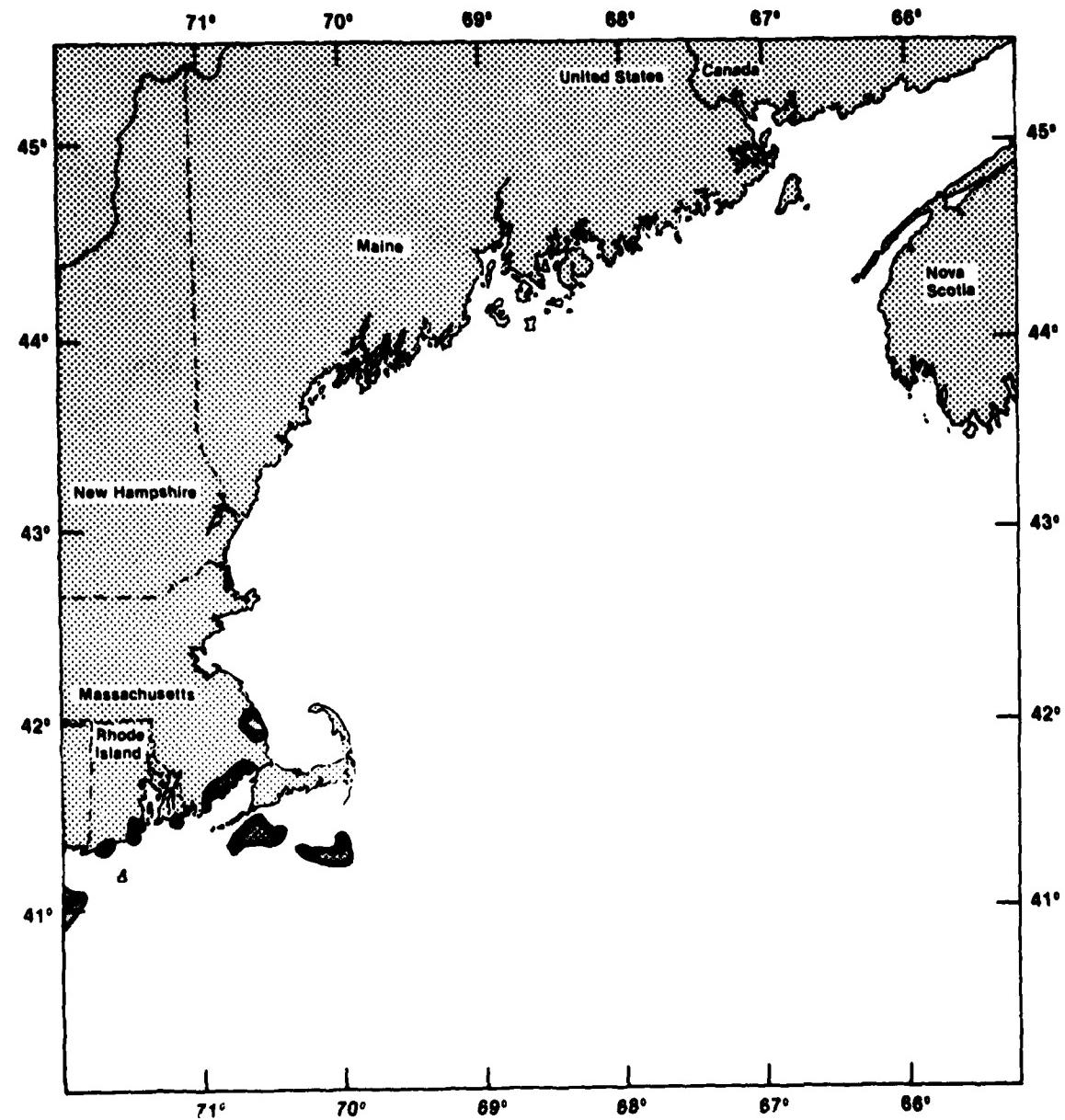


Figure 139.--Mute Swan - Winter and Breeding Areas (after Ray and Dobbin, 1980).

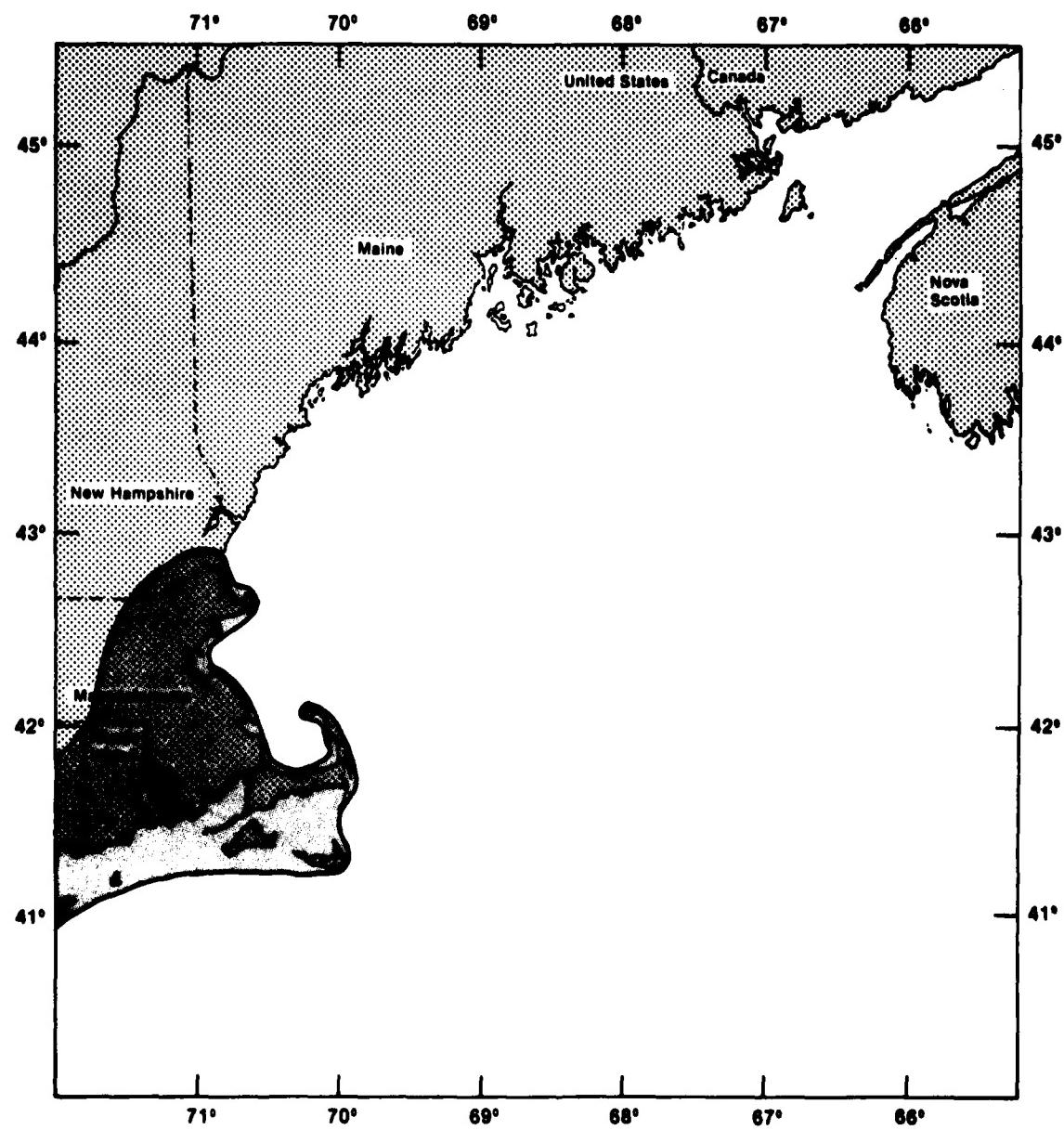


Figure 140.--Canada Goose Winter Area (after Ray and Dobbin, 1980).

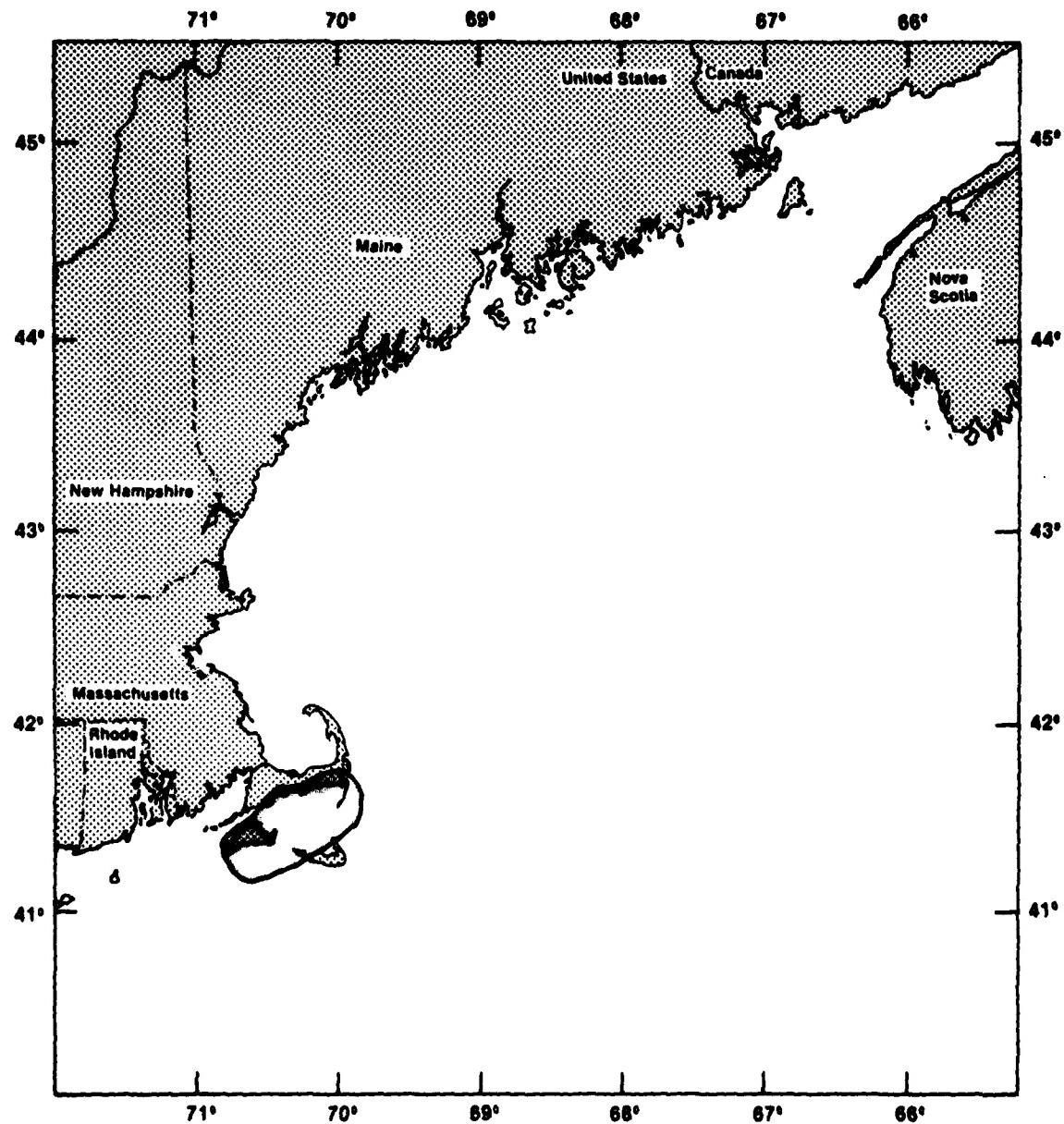


Figure 141.--Atlantic Brant Winter Area (after Ray and Dobbin, 1980).

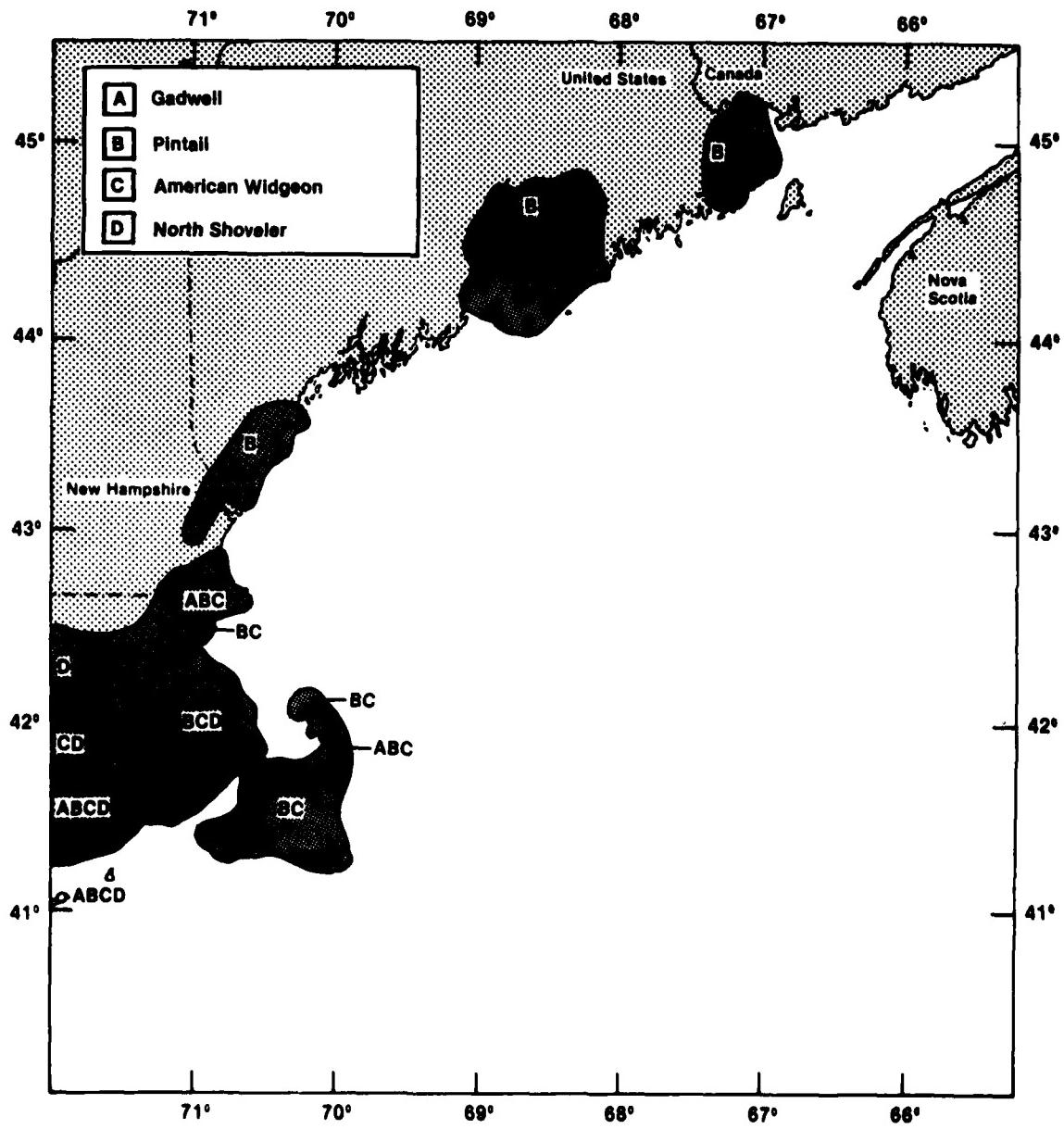


Figure 142.--Surface-feeding Ducks: Winter Distribution (after Ray and Dobbin, 1980).

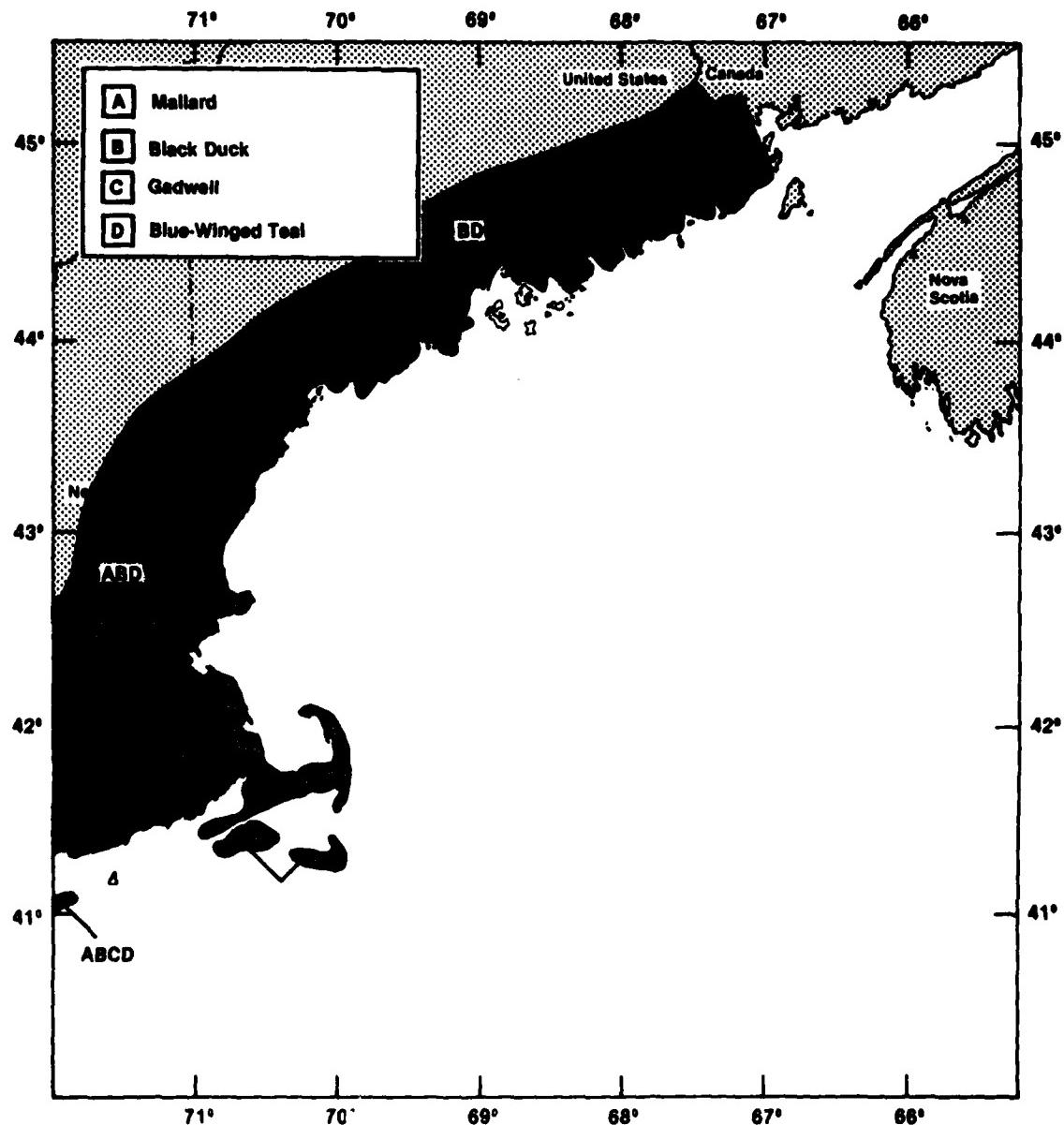


Figure 143.--Surface-feeding Ducks: Winter Distribution (after Ray and Dobbin, 1980).

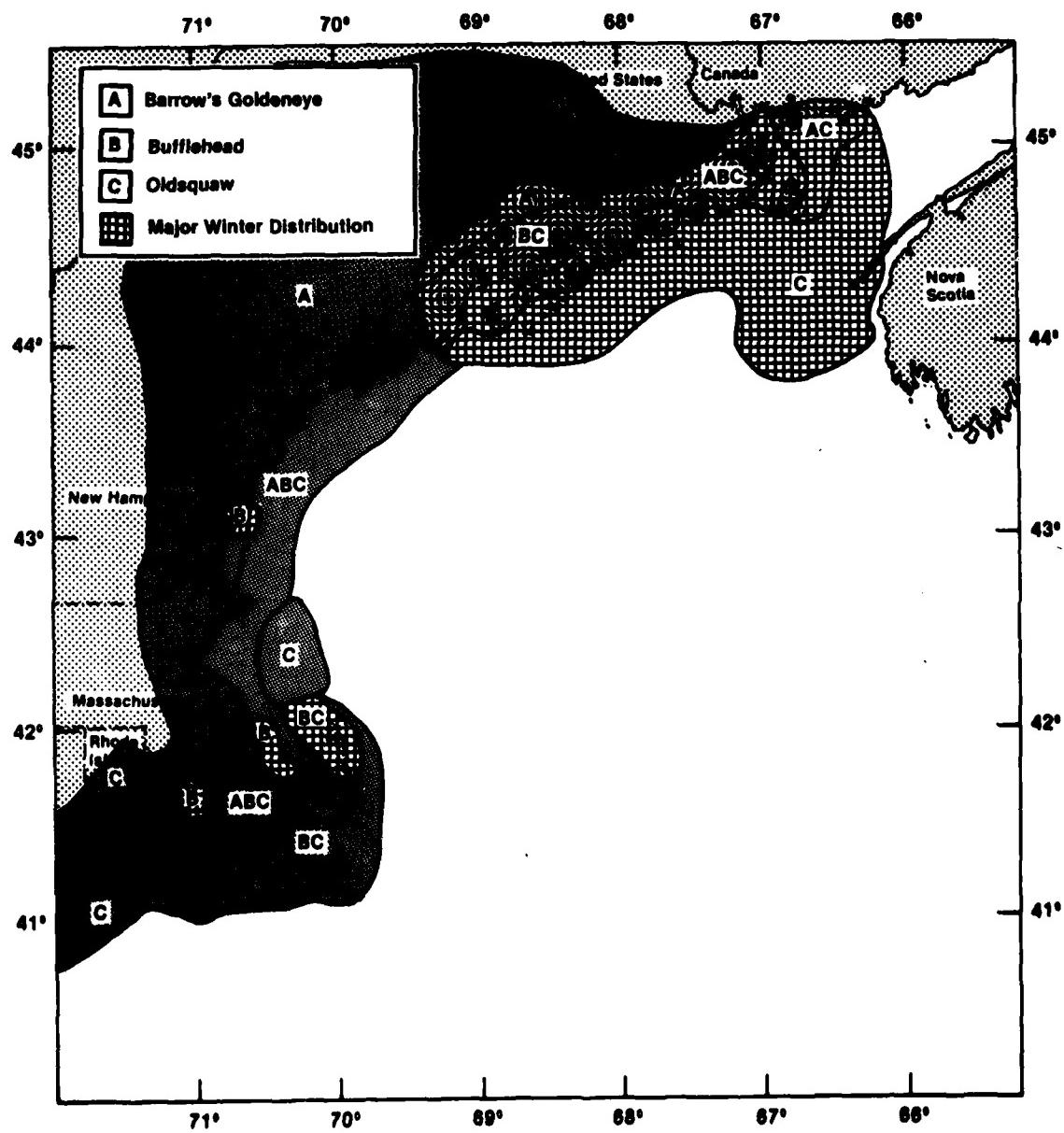


Figure 144.--Water fowl: Winter Distribution (after Ray and Dobbin, 1980).

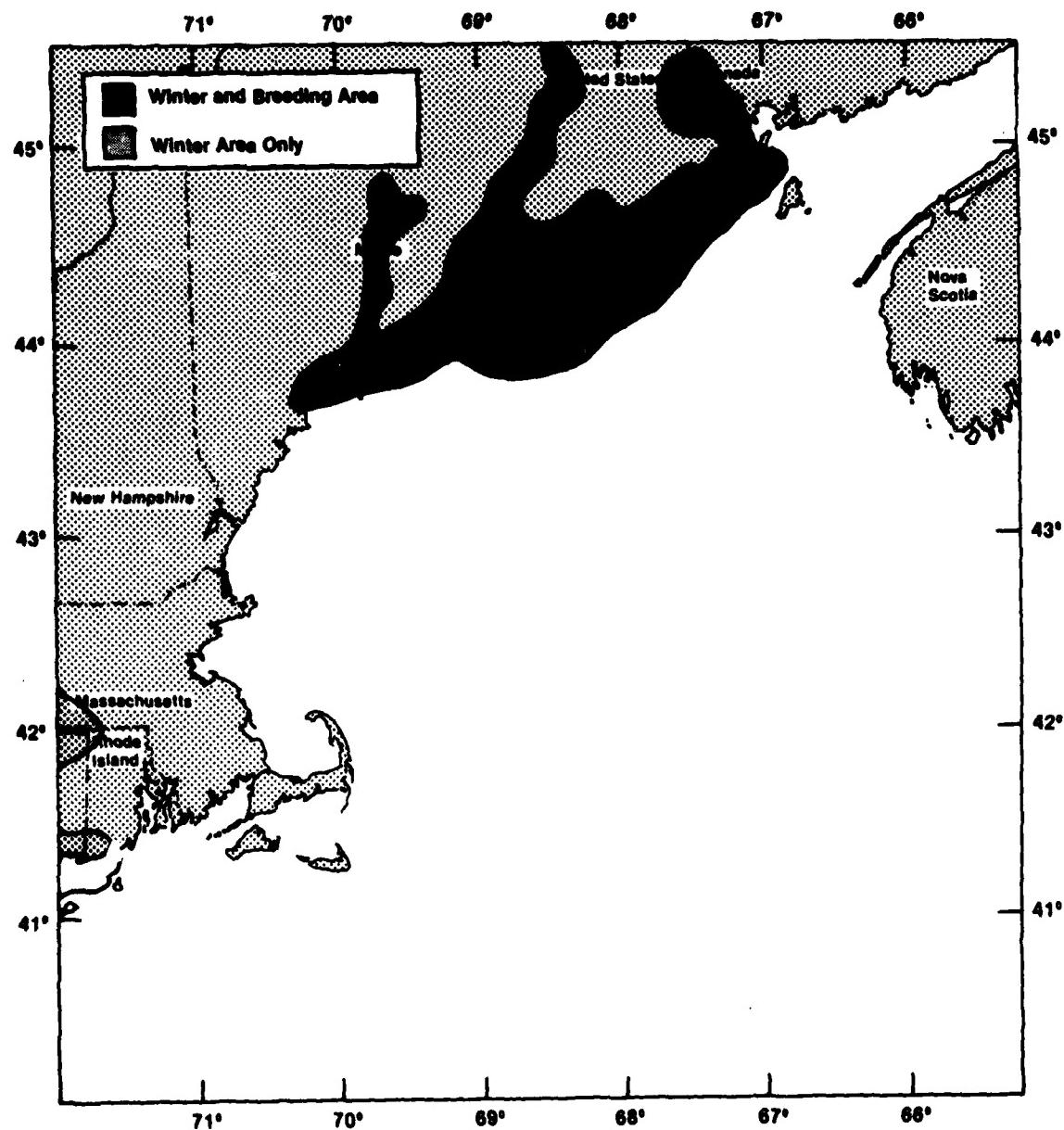


Figure 145.--Bald Eagle Distribution (after Ray and Dobbin, 1980).

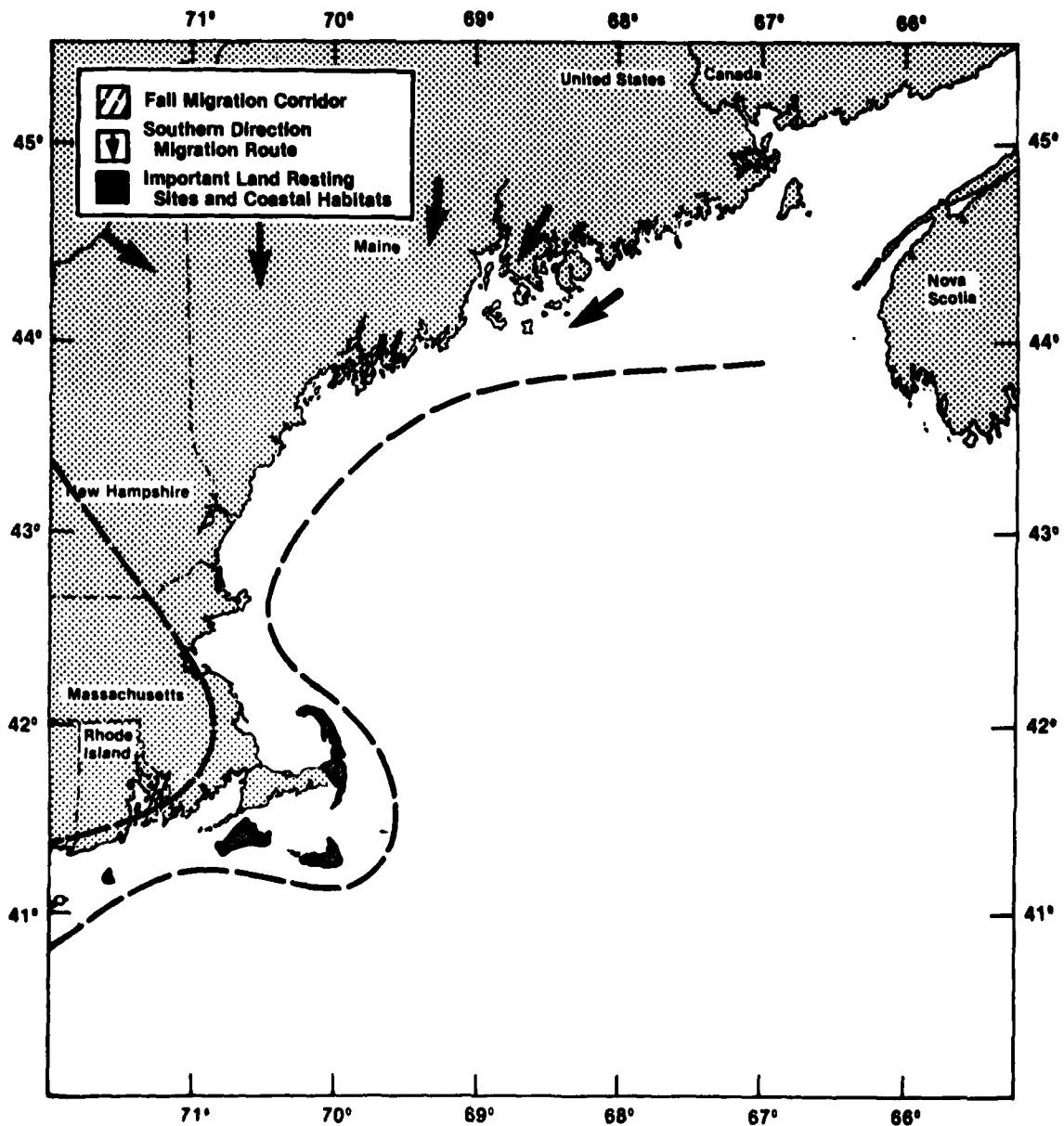


Figure 46. --Perigrine Falcon Distribution (after Ray and Dobbin, 1980).

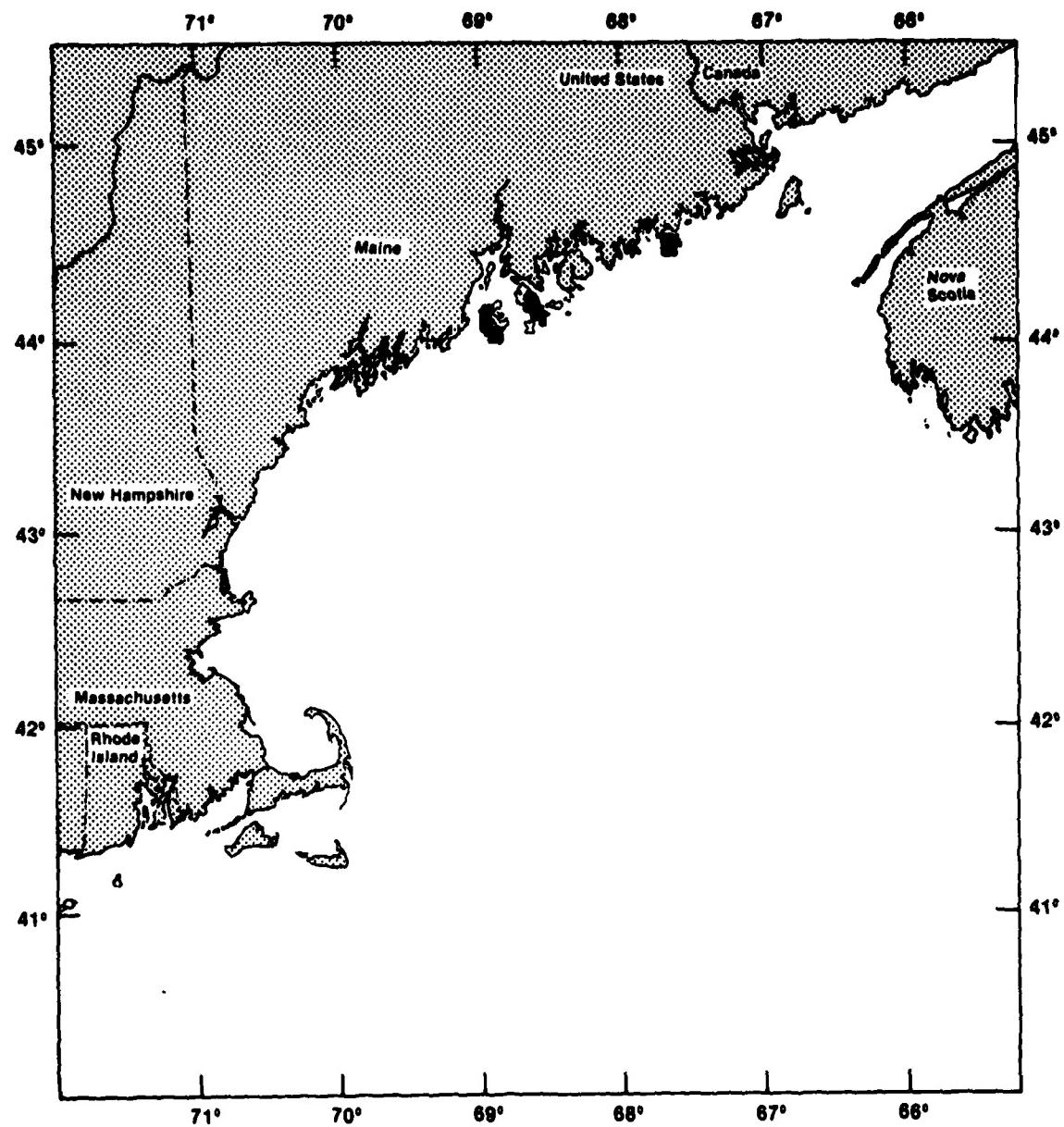


Figure 147.--Kelp Beds (after Smith, Slack and Davis, 1976).

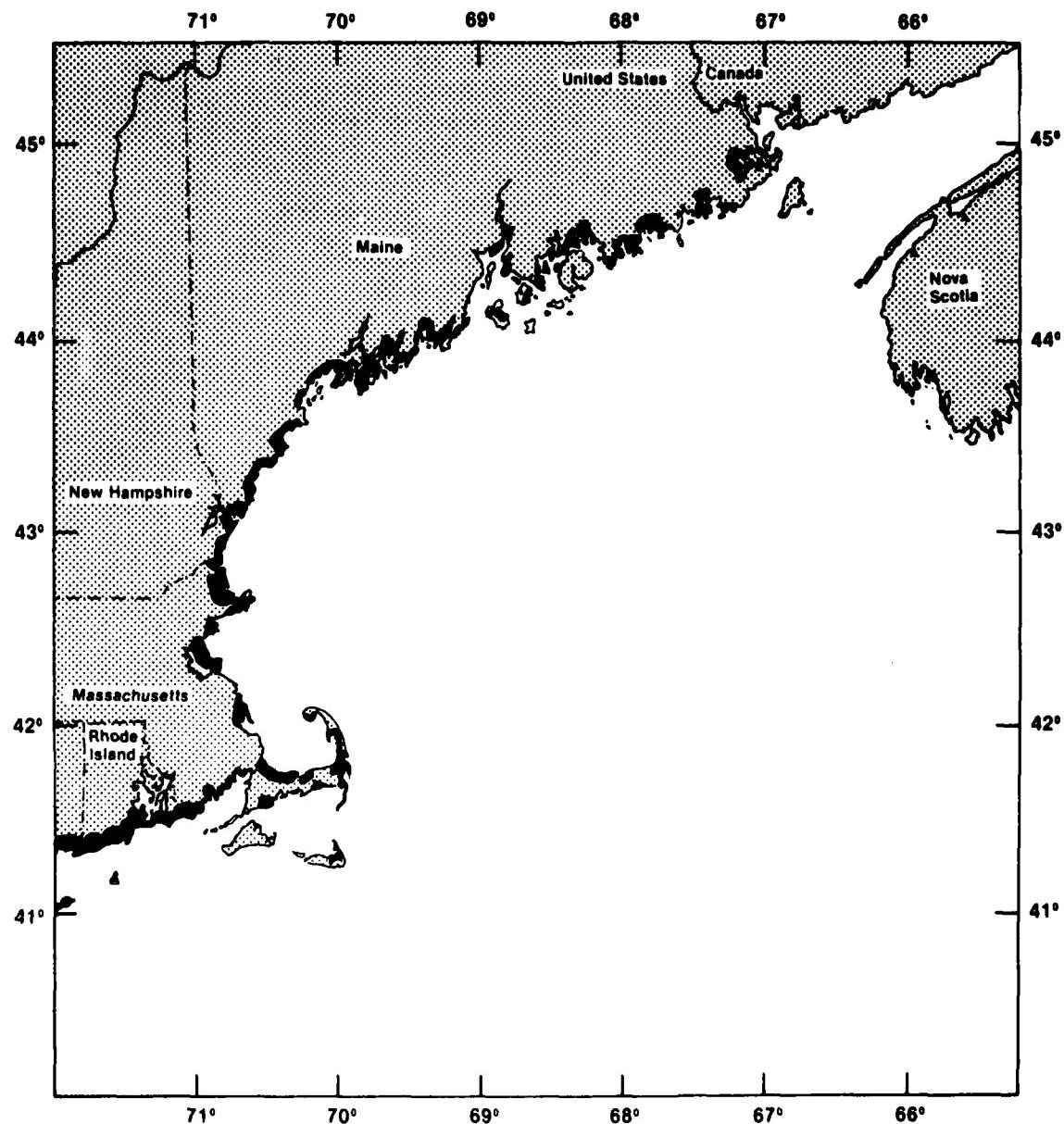


Figure 148.--Salt Marshes (after Smith, Slack and Davis, 1976).

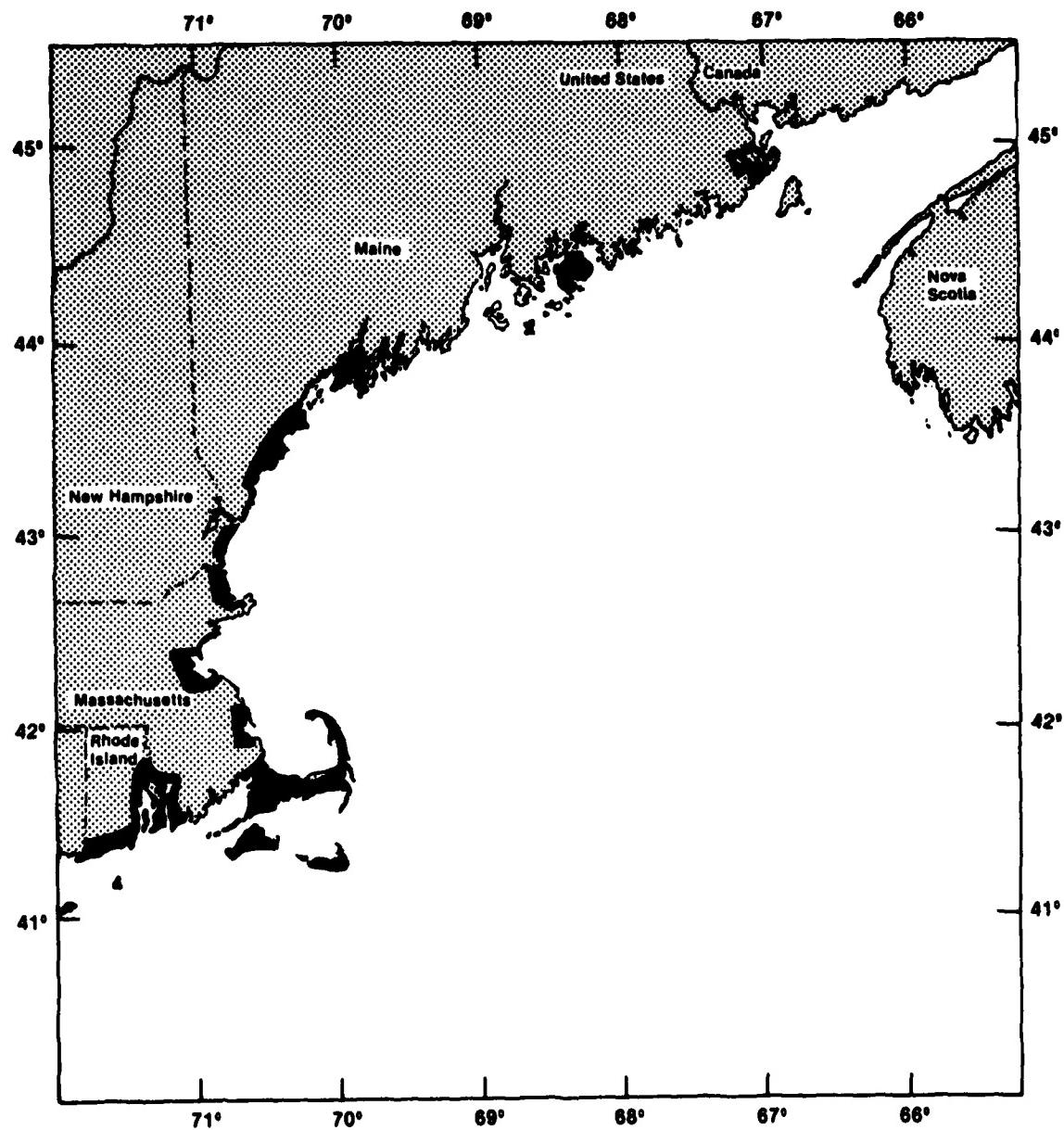


Figure 149.--Beaches and Recreation Areas (after Smith, Slack and Davis, 1976).

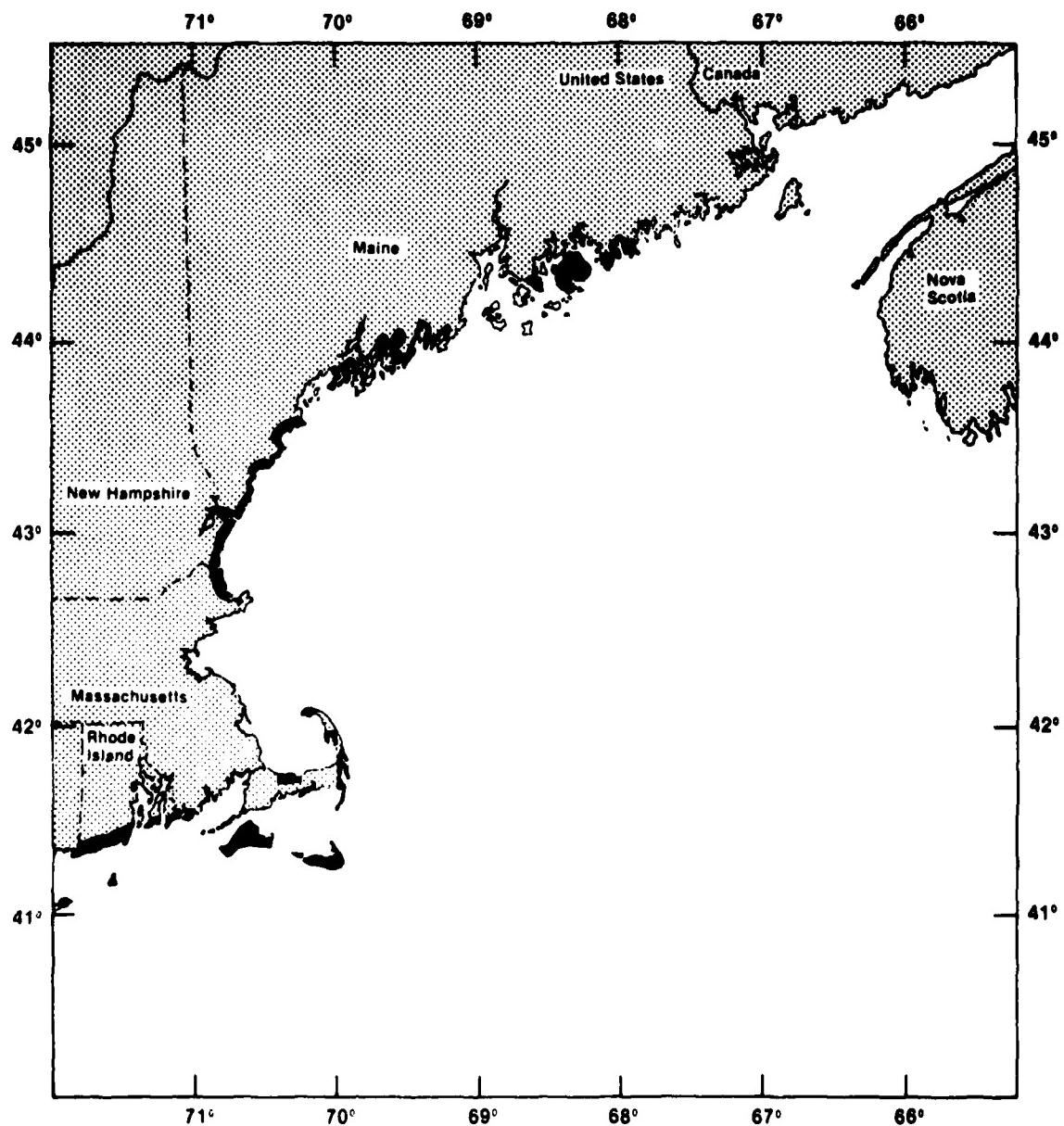


Figure 150.--Wildlife Sanctuaries and Wintering Areas (after Smith, Slack, and Davis, 1976).

**4. DATA AND SUPPORT FOR ACTUAL SPILLS OR OIL SPILL PLANNING**

**a. Climatological Modeling**

Chief, Marine Environmental Assessment Division  
NOAA/EDIS/CEAS, D23  
3300 Whitehaven St., N.W.  
Washington, D.C. 20235  
202/634-7381

**b. Oceanographic Data Archives**

Director, National Oceanographic Data Center  
NOAA/EDIS/NODC, D7  
2001 Wisconsin Avenue, N.W.  
Washington, D.C. 20235  
202/634-7232

**c. Meteorological Data Archives**

Director, National Climatic Center  
NOAA/EDIS/NCC, D5  
Federal Bldg.  
Asheville, NC 28801  
704/258-2850

**d. Operational Marine Forecasts (including oil spills)**

Director, Techniques Development Lab.  
NOAA/NWS/TDL, W42  
Gramax Building  
8060 13th Street  
Silver Spring, MD 20910  
301/427-7613

**e. Single Event Modeling, Advice and Forecasts**

Chief, Oil Spill Scientific Support Team (NOAA)  
7600 Sand Point Way, NE  
Building 264 SW  
Seattle, Washington 98115  
(FTS) 399-5919

**f. Marine Ocean Forecasts**

Chief, Ocean Services Division (NOAA)  
Gramax Building  
8060 13th Street  
Silver Spring, MD 20910  
301/427-7778

**g. Comprehensive Emergency Management of Hazardous Materials Spills**

Dr. Joseph M. Bishop  
Federal Emergency Management Agency  
Washington, DC 20472  
566-0760

## 5. ACKNOWLEDGEMENTS

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This project has been transferred to the Federal Emergency Management Agency (FEMA). Reviewers at FEMA include Dr. Frank Hersman, Mr. John Gibson, Ms. Sue Perez, Mr. Bill Mayers, Mr. Bill Monahan and Ms. Peg Malloy.

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